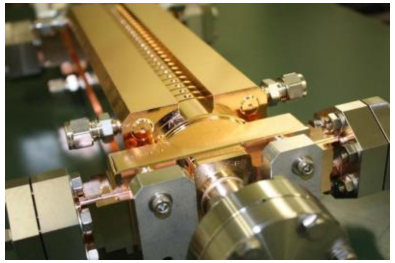
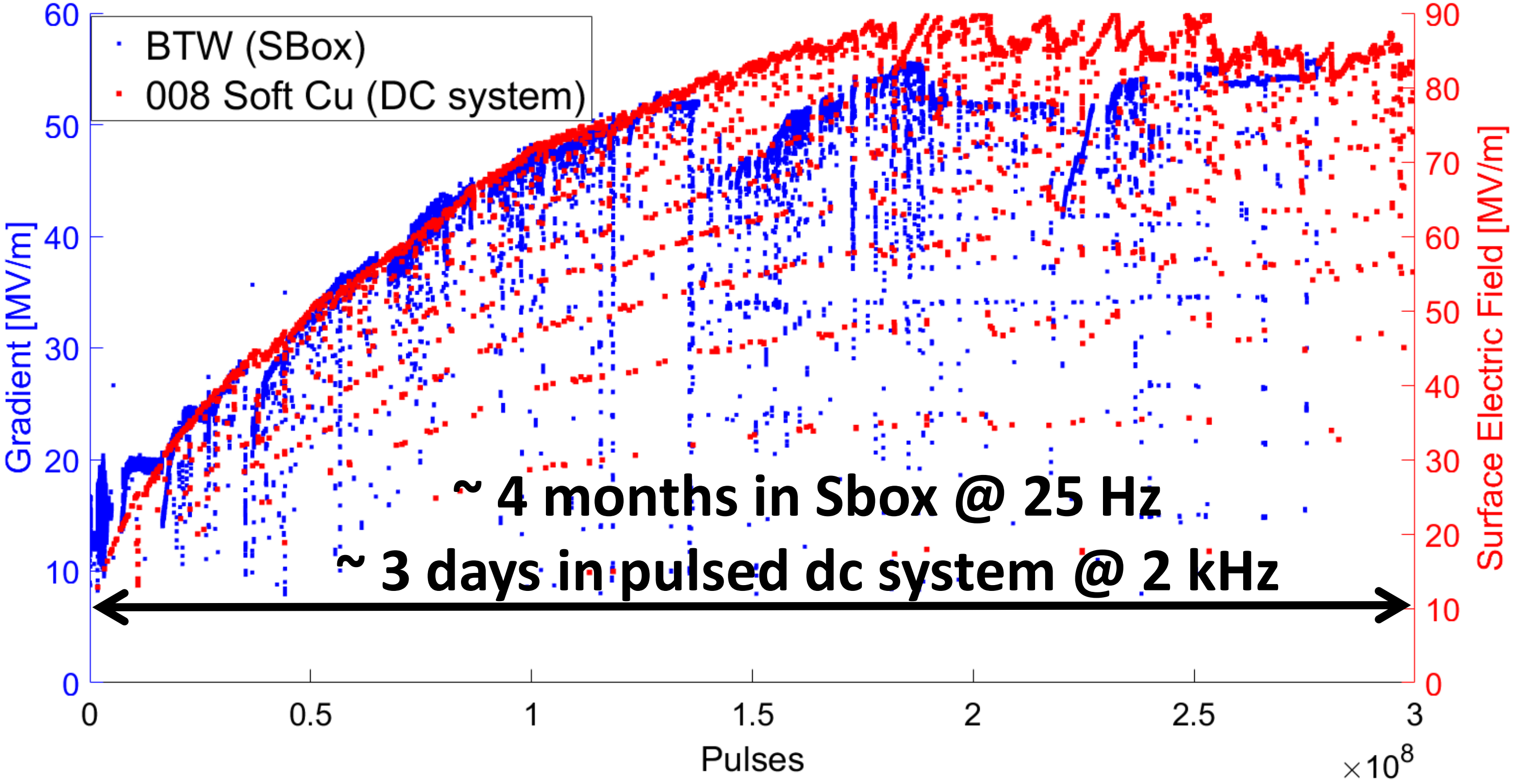
High-field measurements with kHz repetition rate, microsecond dc pulses

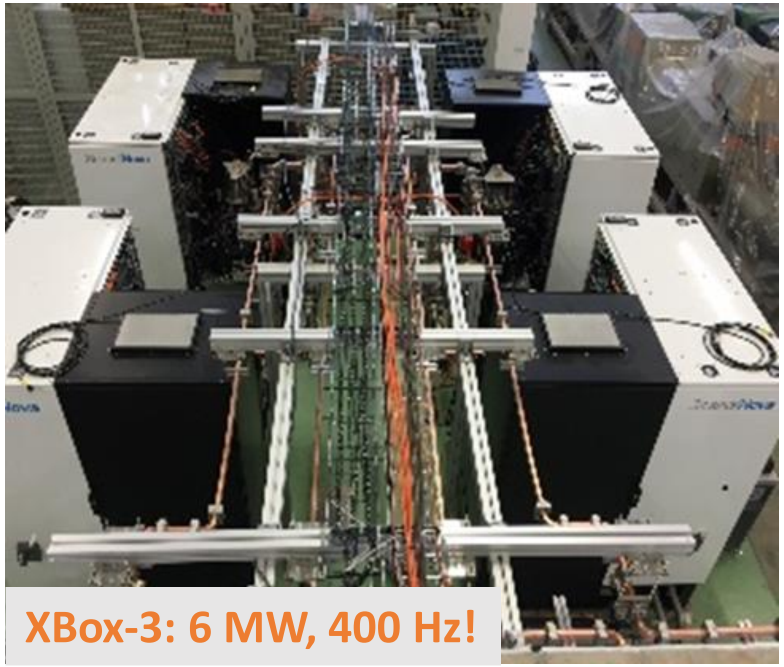
Iaroslava Profatilova

Conditioning in RF and DC



Marx generator, 6kHz





XBox-3: 6 MW, 400 Hz!

...courtesy of Xboxes team

Comparison of heat-treated and as-machined copper

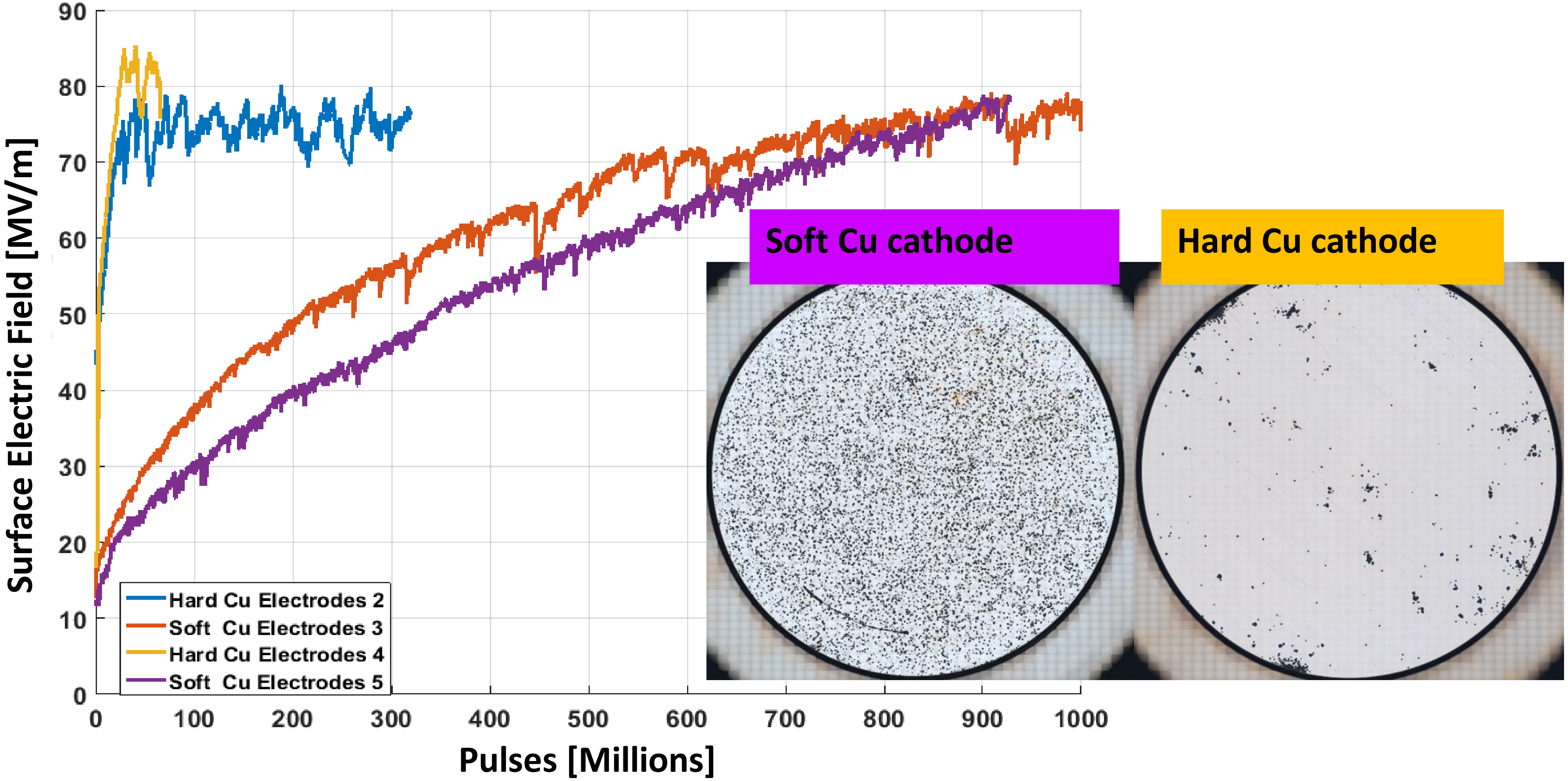
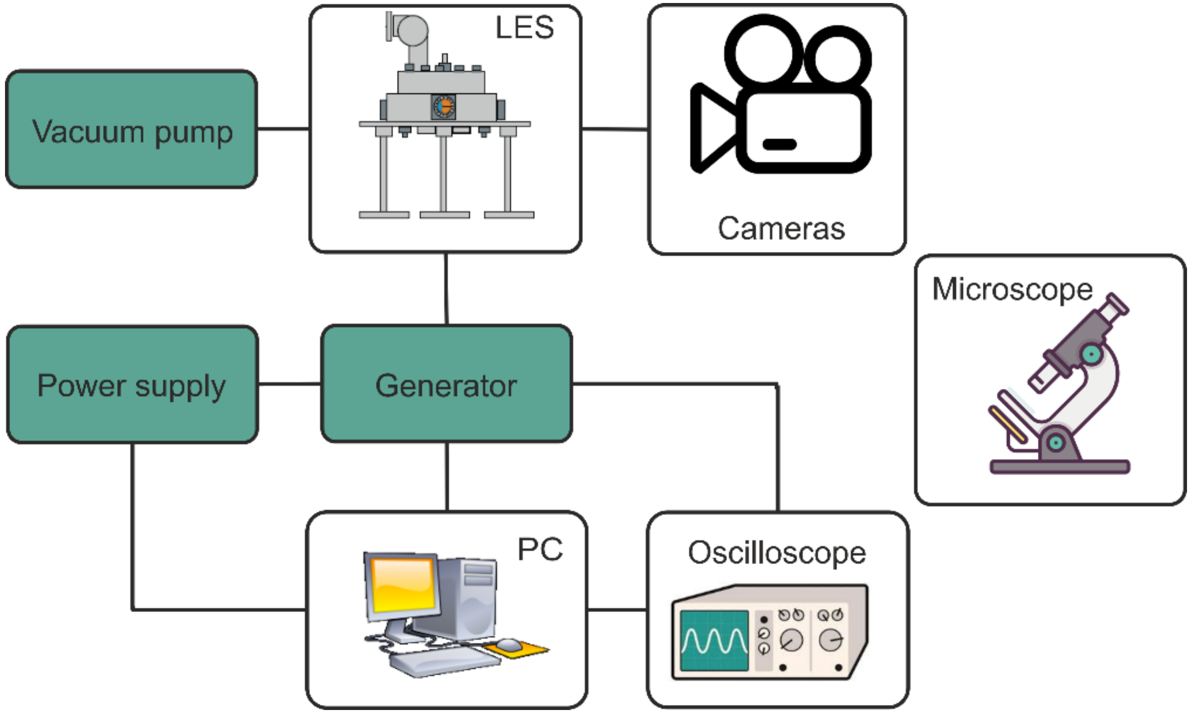


Fig. 3. Conditioning curves from tests at Pulsed DC System taken with HRR circuit, 16.7 µs pulse lengths and 60 µm gap distances.

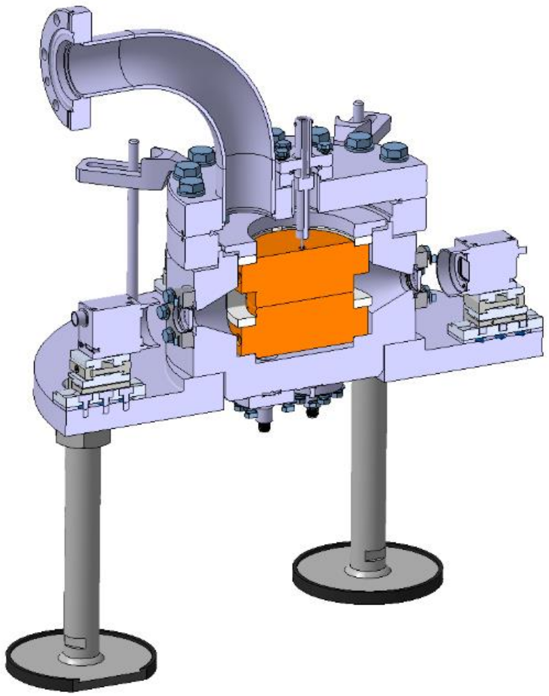
Pulsed DC System

vacuum system for high-gradient studies



a)

b)



c)

Fig. 4. Pulsed DC system at CERN: a) schematic of the equipment, b) photo of Large Electrodes System (LES), c) 3D-model for LES.

Marx generator

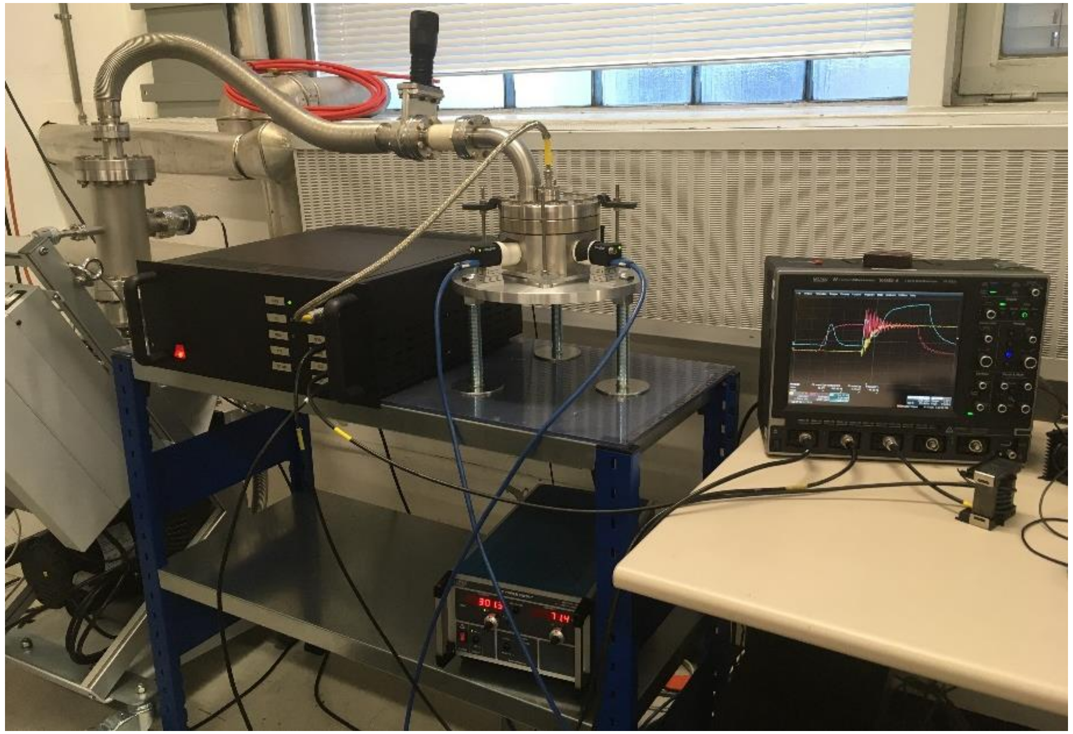


Fig. 5.1. Photo of Marx generator together with LES.

Repetition rate: up to 6 kHz
Pulse length: 500 ns – 1 ms.

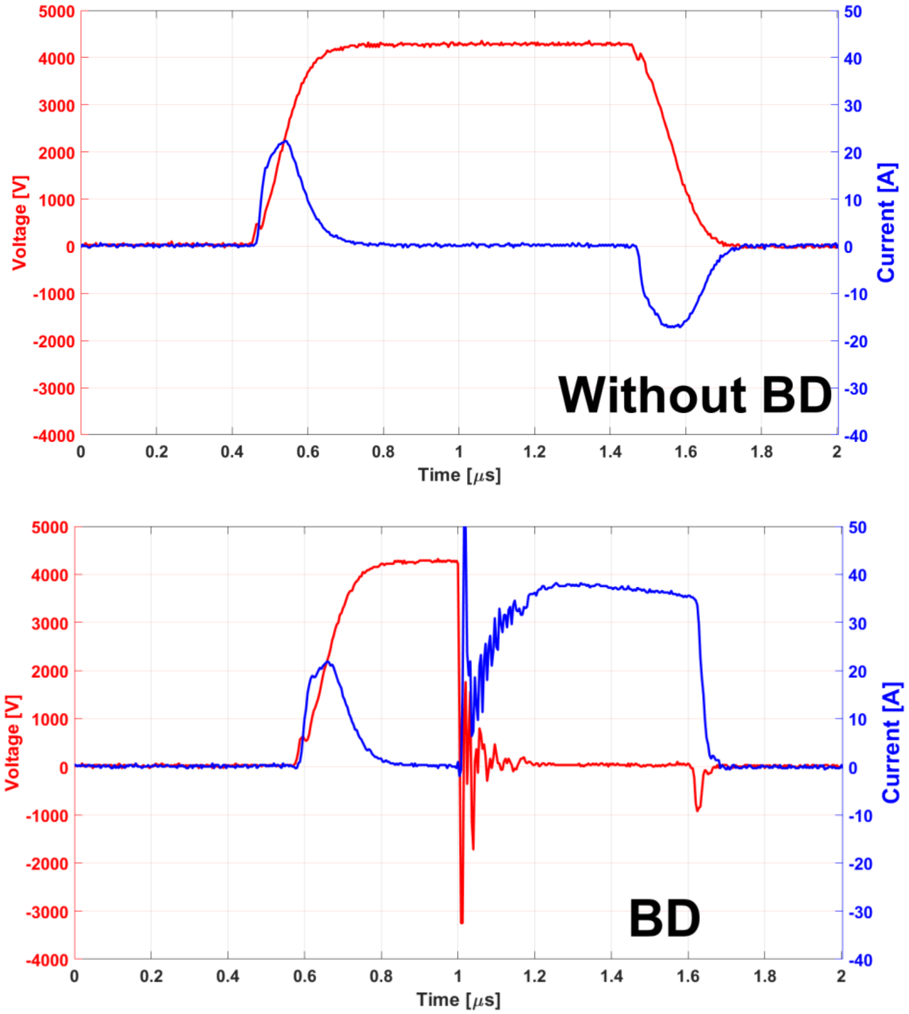


Fig. 5.2. The waveforms taken with Marx generator and LES with 1 μs pulse (0.6 μs delay is used in BD case).

Different tests in pulsed DC system

- **Conditioning**
- **Polarity changing**

Feedback mode

- **BDR vs Surface electric field**
- **BDR vs Pulse width**
- **BDR vs Rep Rate**

Flat mode

Conditioning for different materials

Motivation: Feedback mode

- This algorithm was implemented at Pulsed DC system to be similar to RF test.
- The conditioning is needed for training of materials to be able to reached higher electrical field.

Table 1. The example of parameters for conditioning test.

Parameter	Value
Max number of pulses per cycle	100 000
Safe pulses	20 000
Gain voltage at 0	-10 V
Gain after timeout	10 V
Initial voltage	600 V (~10 MV/m)
Max BDR	5E-5

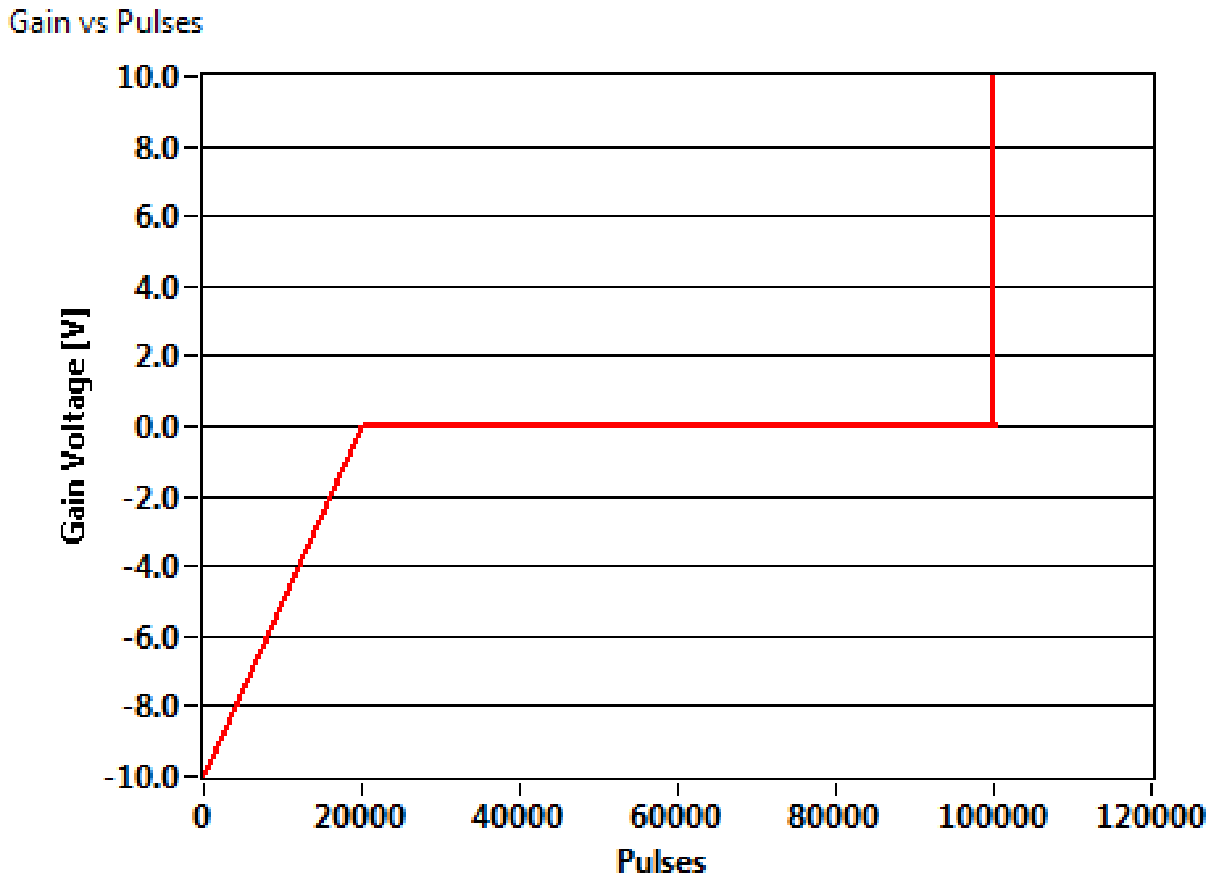


Fig. 7. Visualization of conditioning algorithm.

Recovering after BD (ramp)

Motivation:

- To see if we can reduce the time needed for recovering after BD.

For flat and feedback modes

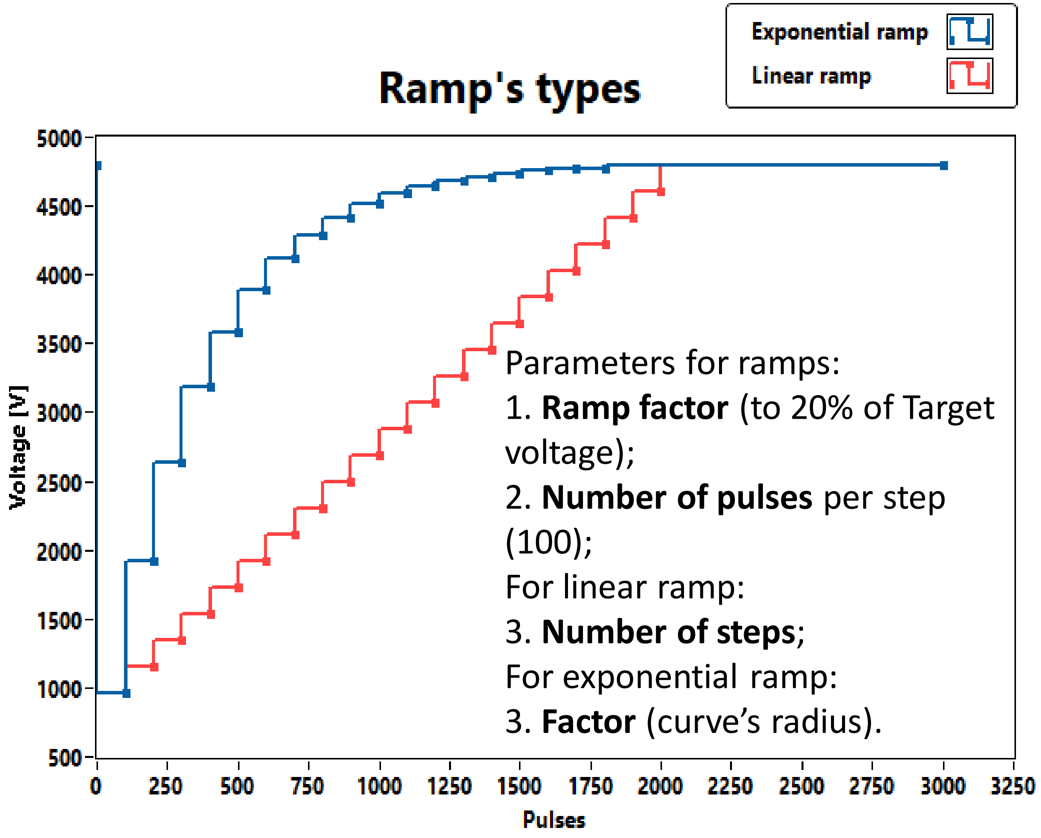


Fig. 8.1. The explanation of algorithms.

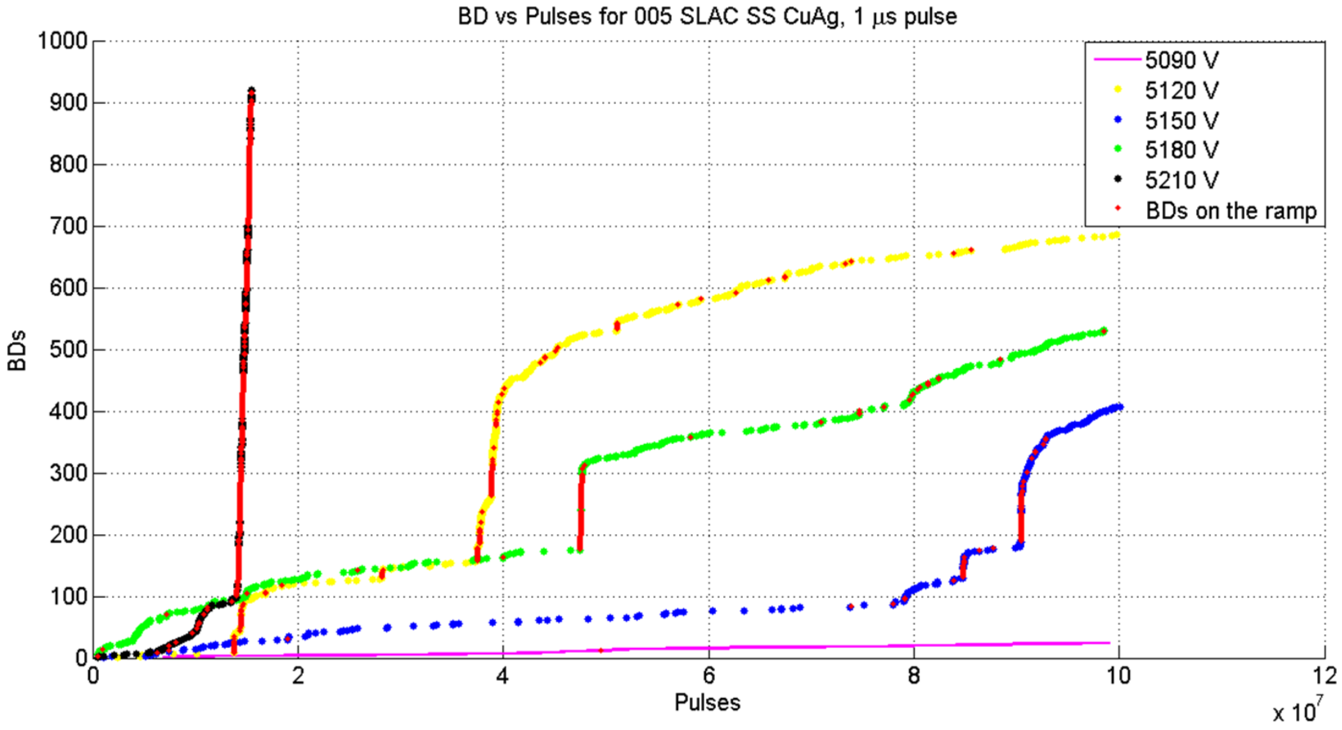
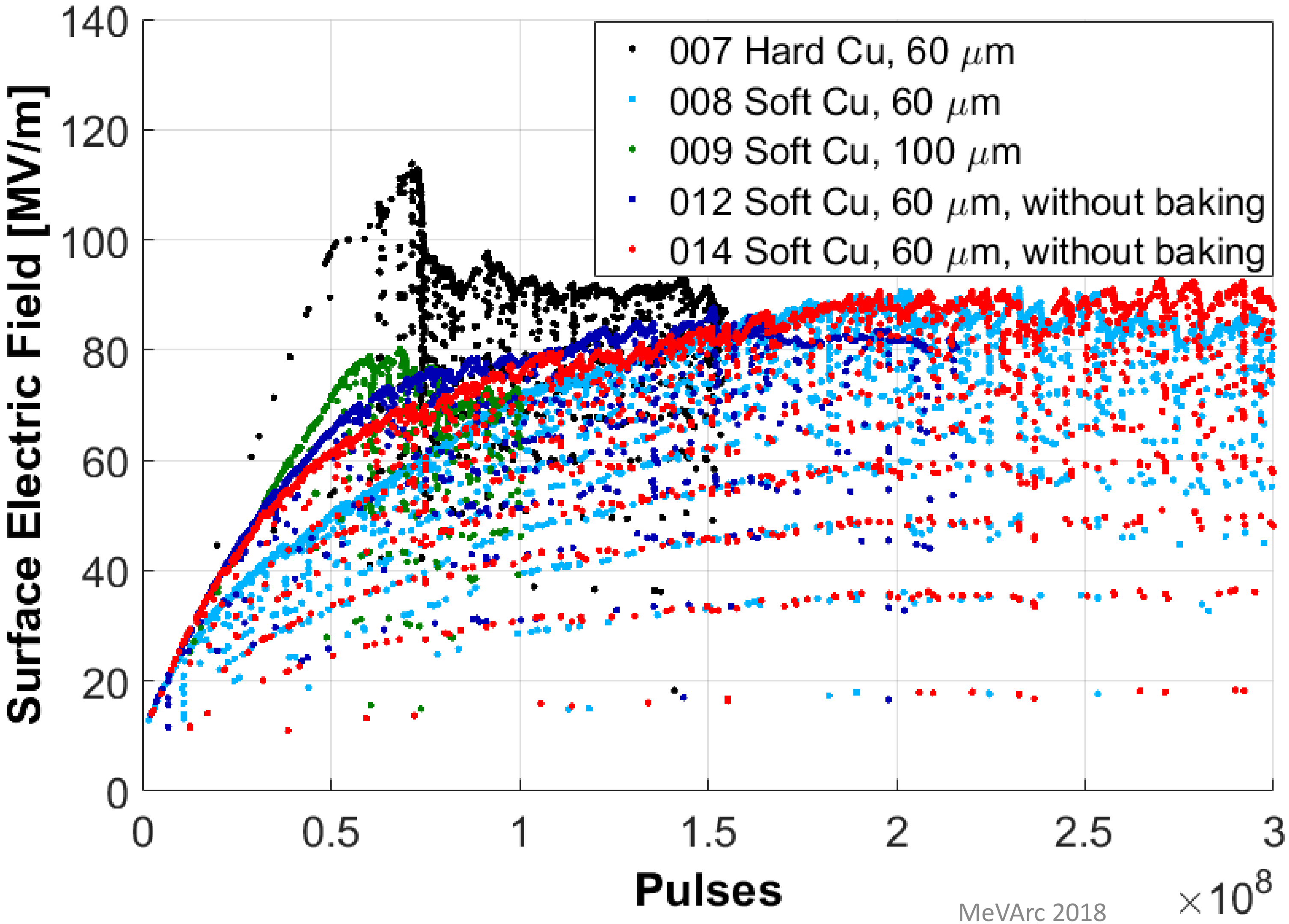


Fig. 8.2. Effect of ramp to the results.

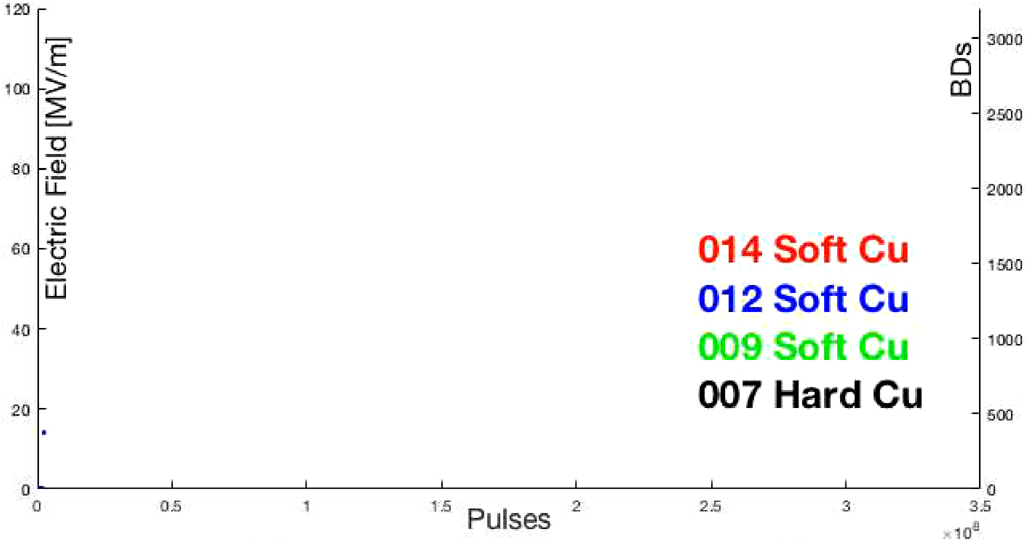
Conditioning for different materials

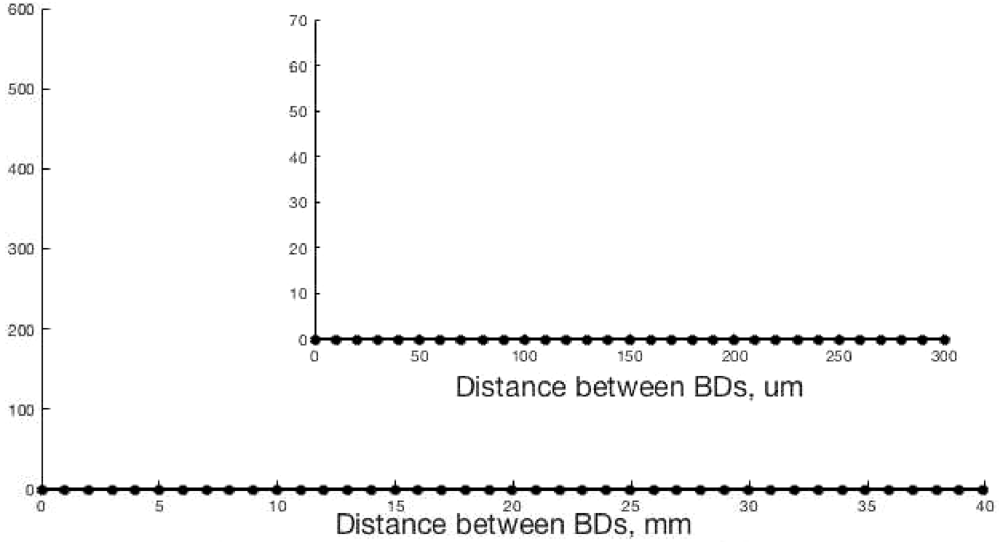


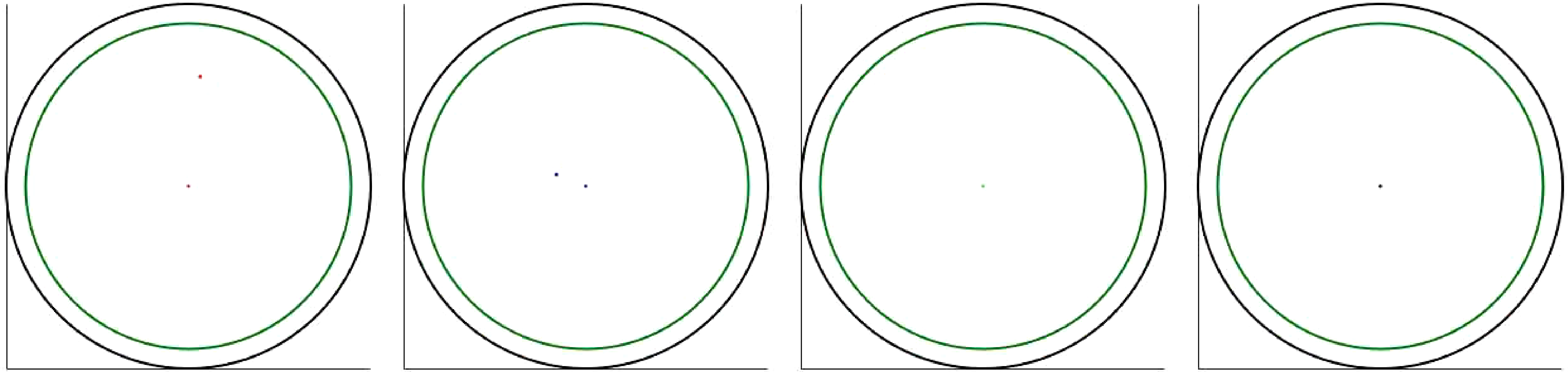
Sample number	Name	"Bonding"	Baking
007	**Hard Cu**	No	No
008	**Soft Cu**	Heated up to 1040°C in hydrogen atmosphere	Baked up to 650°C
009	**Soft Cu**	Heated up to 850°C in hydrogen atmosphere	Baked up to 650°C
012	**Soft Cu**	Heated up to 1040°C in hydrogen atmosphere	No
014	**Soft Cu**	Heated up to 1040°C in hydrogen atmosphere	No

All tests were done under the pressure better that 1E-8 mbar. The parameters for feed back modes are the same for all 4 tests.

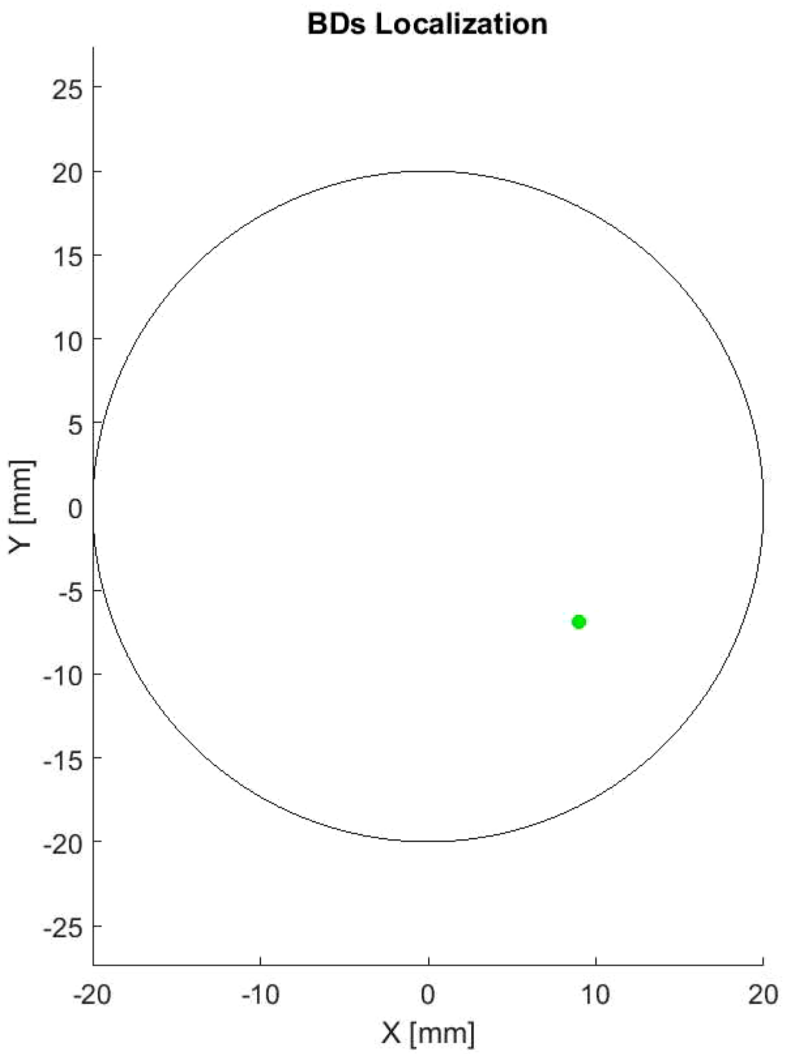
Conditioning progress







BD localization technique



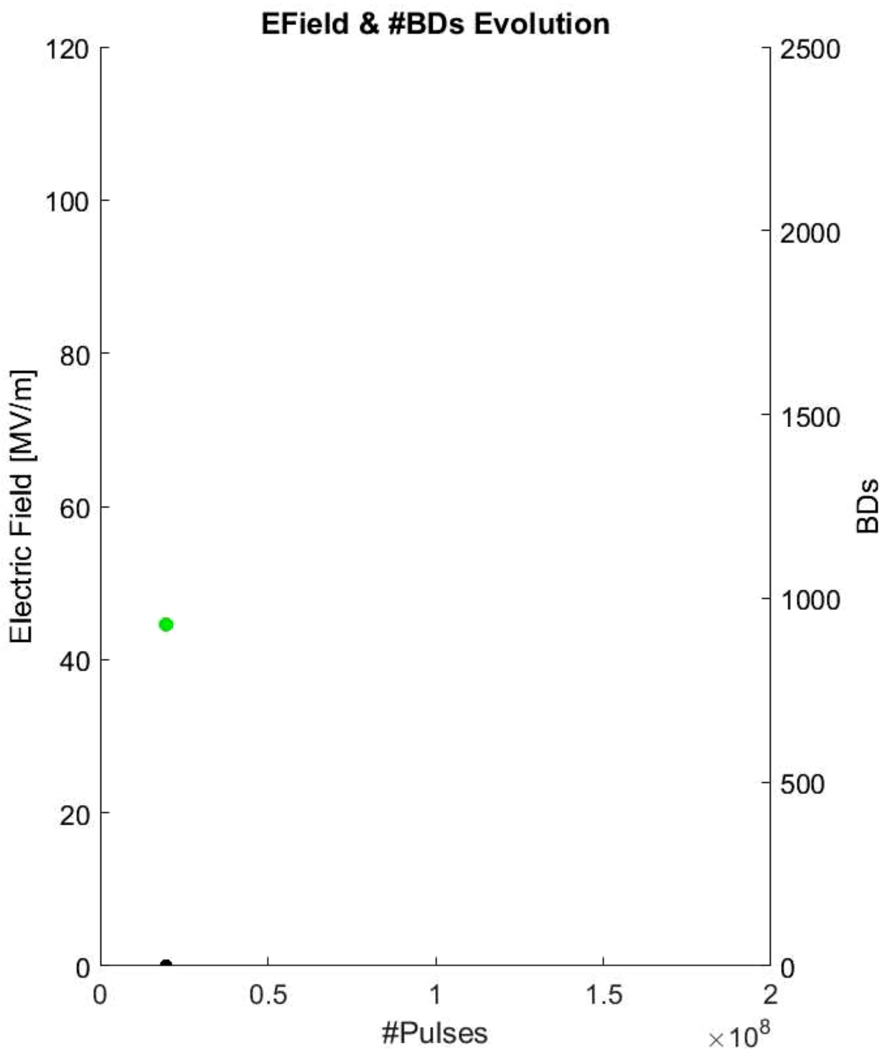
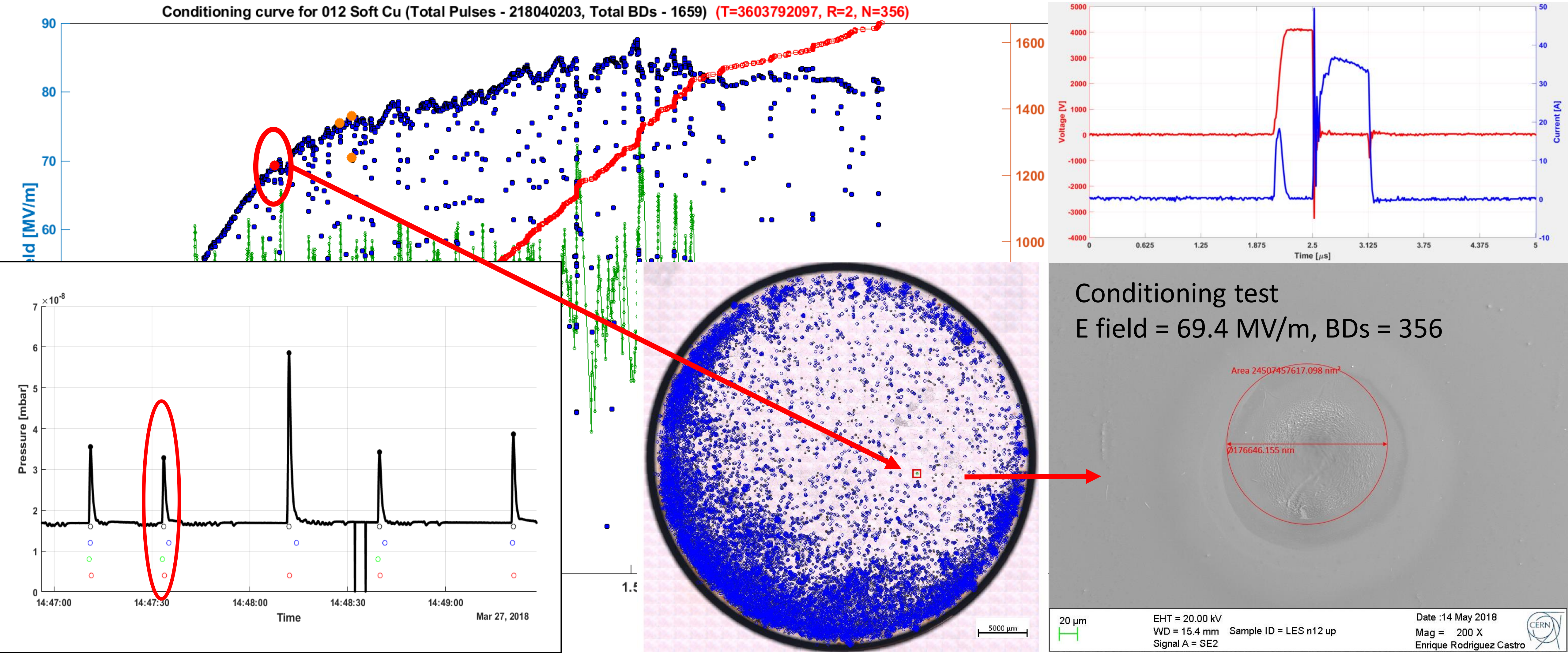


Fig. 11. Visualization of BDs evolution at the surface for **007 Hard Cu** electrodes (video works only in slide show mode (red dots corresponded to BDs occurred at the optimized region.

BD identification



Polarity changing

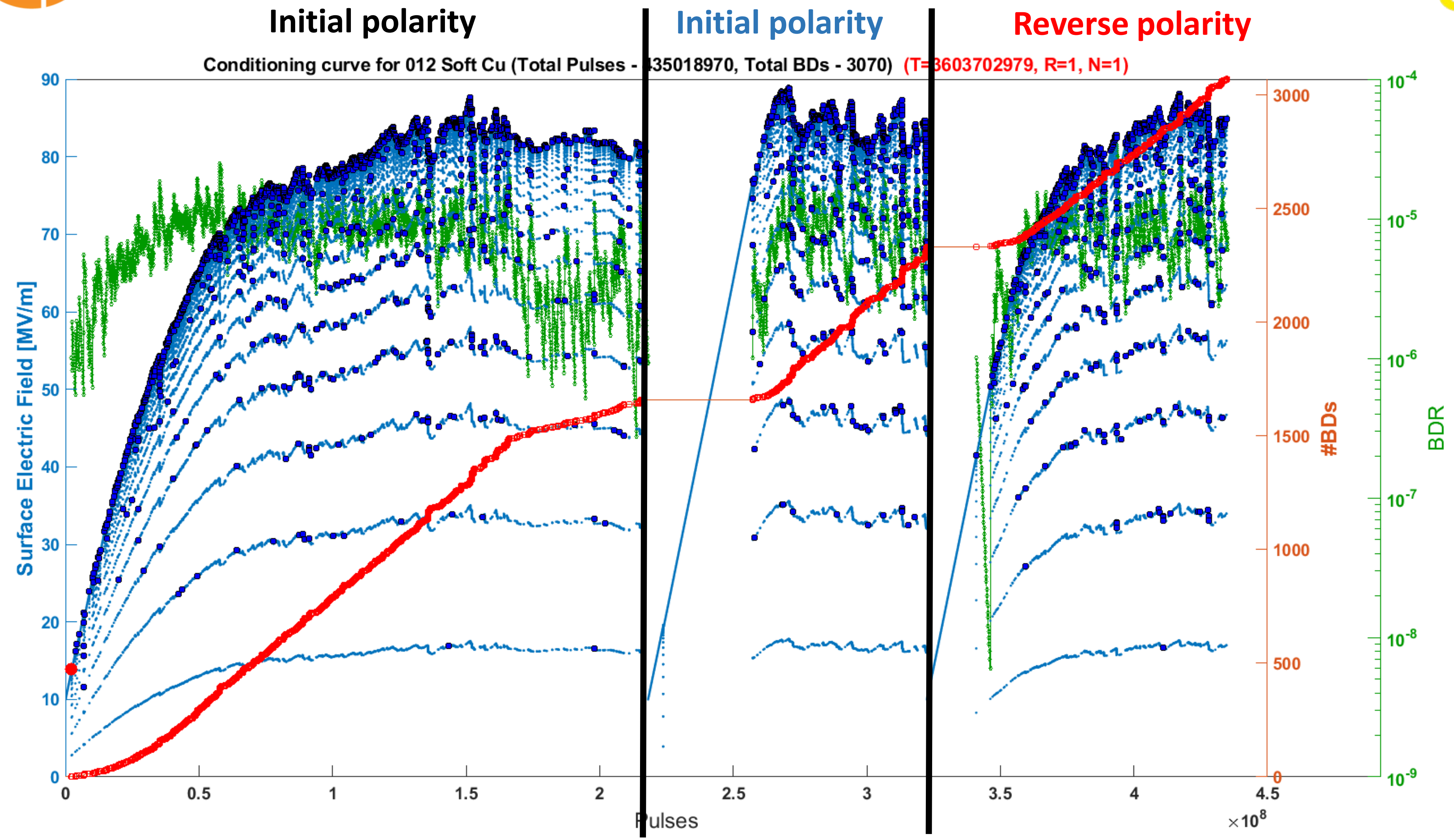
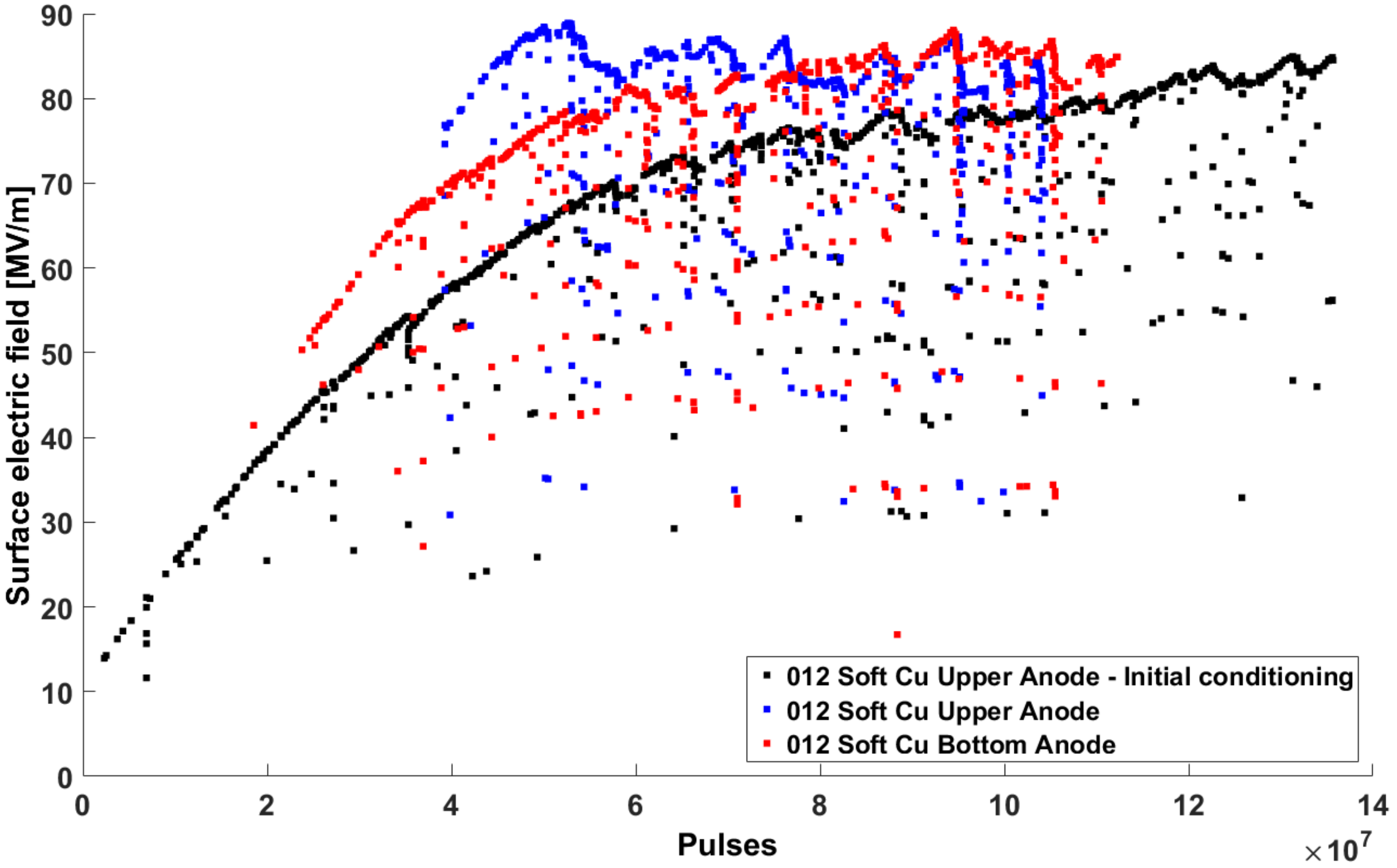
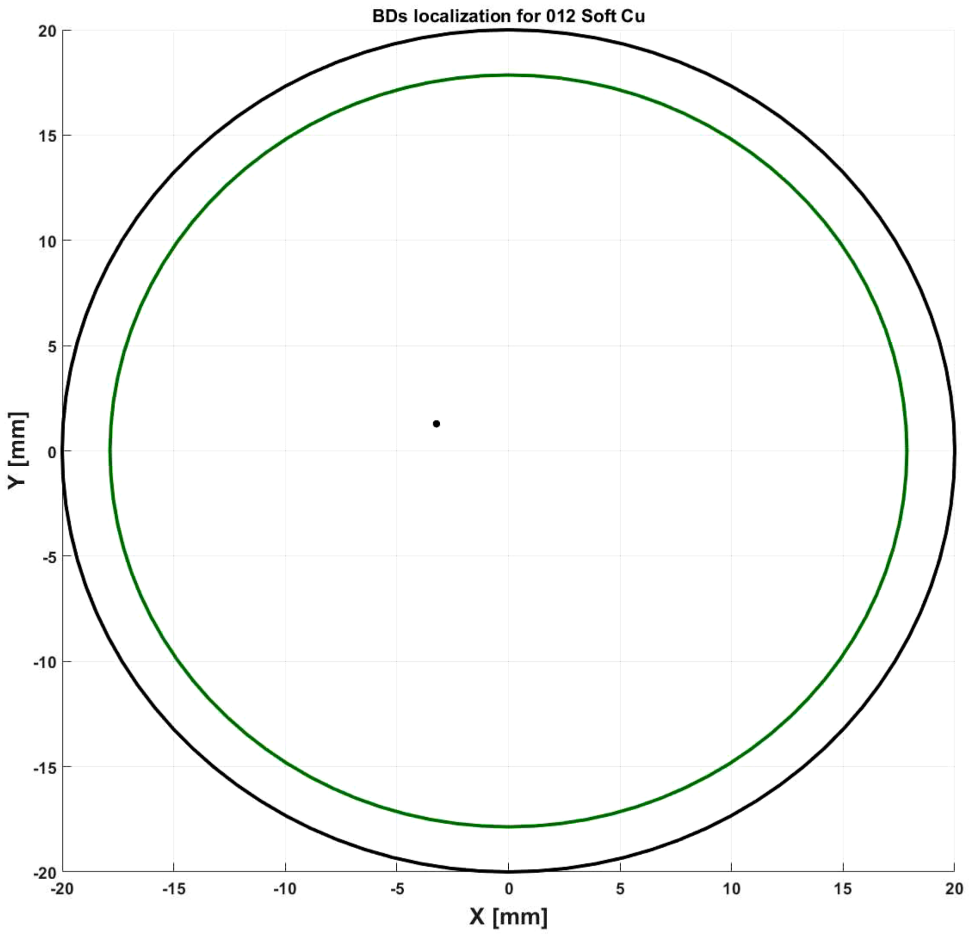


Fig. 13. The consequence of test with different polarities. Test was done with **012 Soft Cu** electrodes,
60 um gap,
1 µs pulse width.

Different polarities





Flat mode

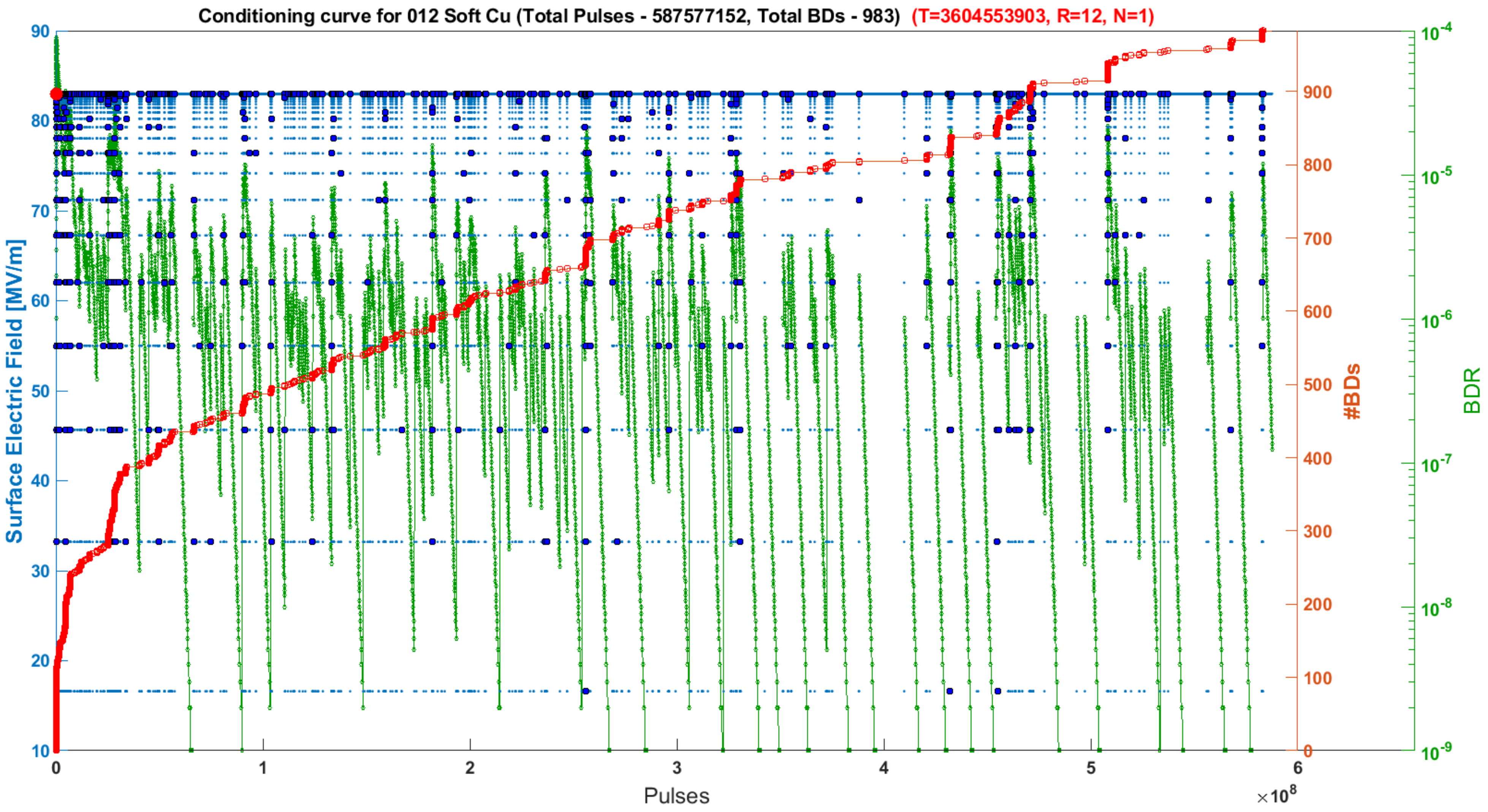
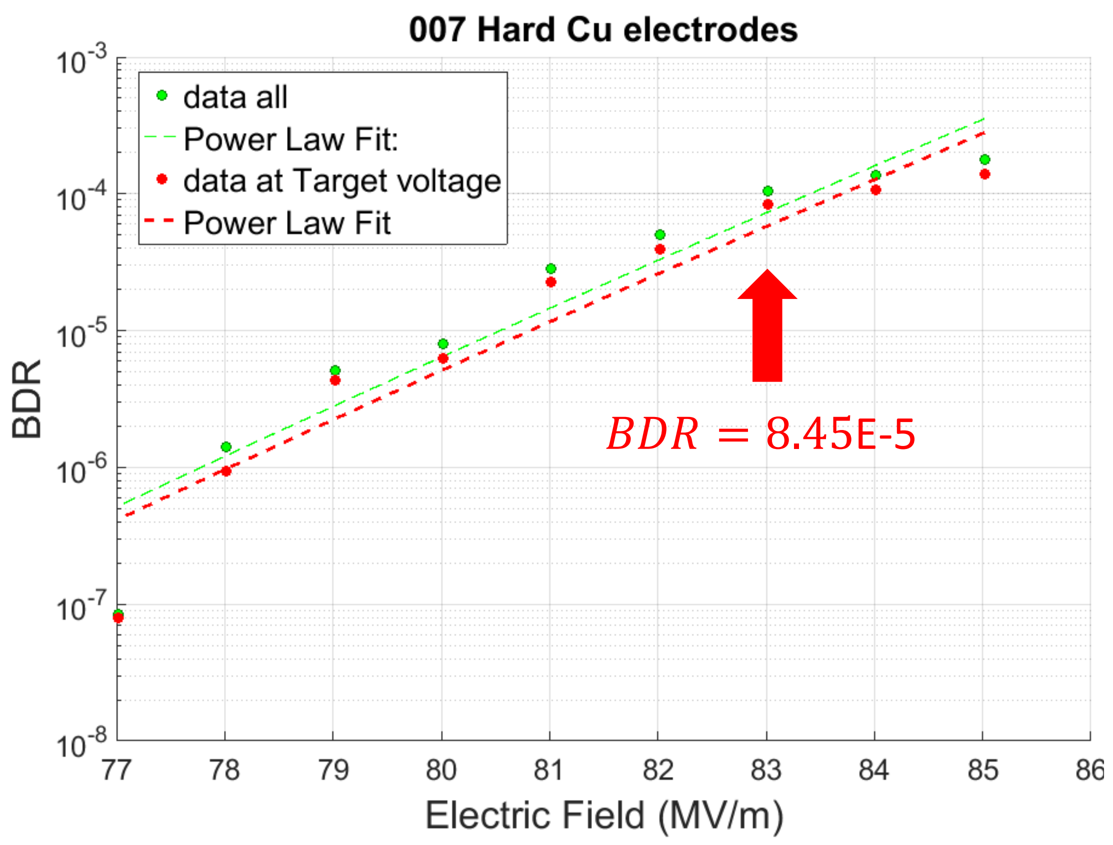


Fig. 15. The test in flat mode with recovering after BD algorithm shown the conditioning over the pulses.

Probability density



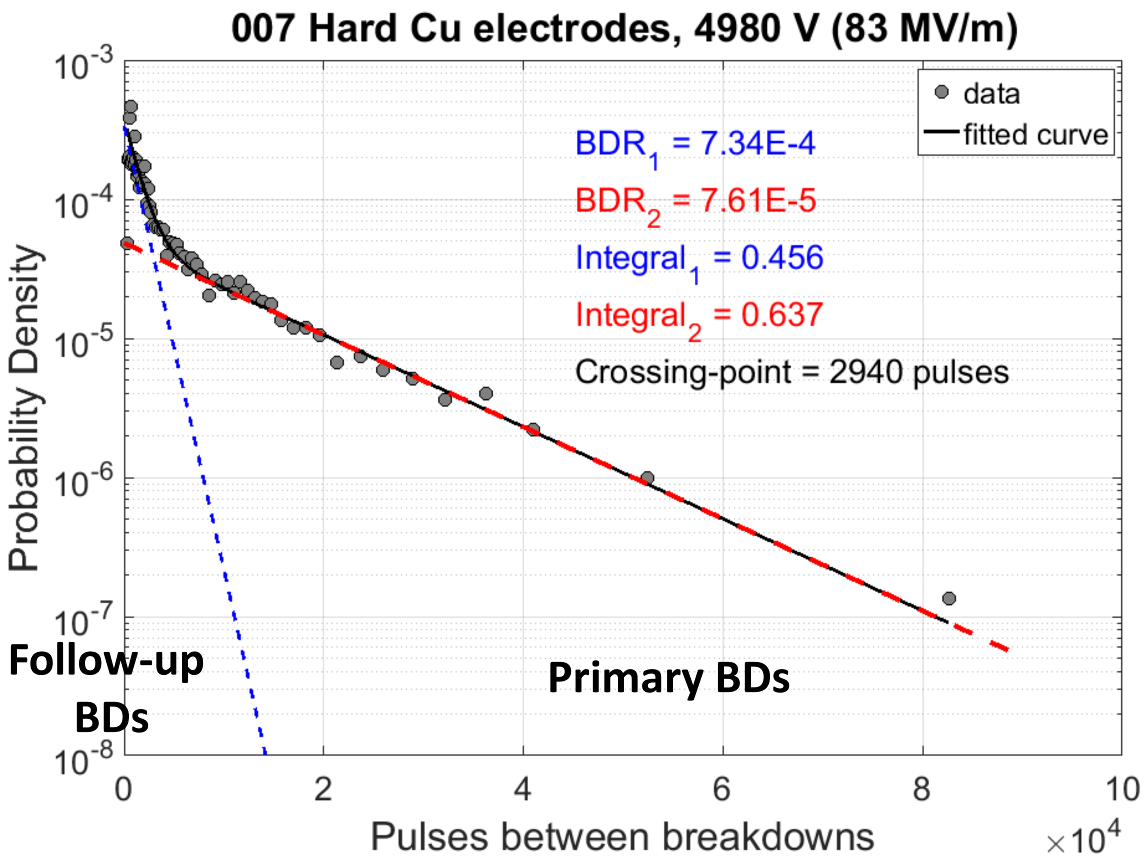


Fig. 16. a) effect of ramp algorithm to results; b) the example of PDF analysis.

BDR vs Surface electric field

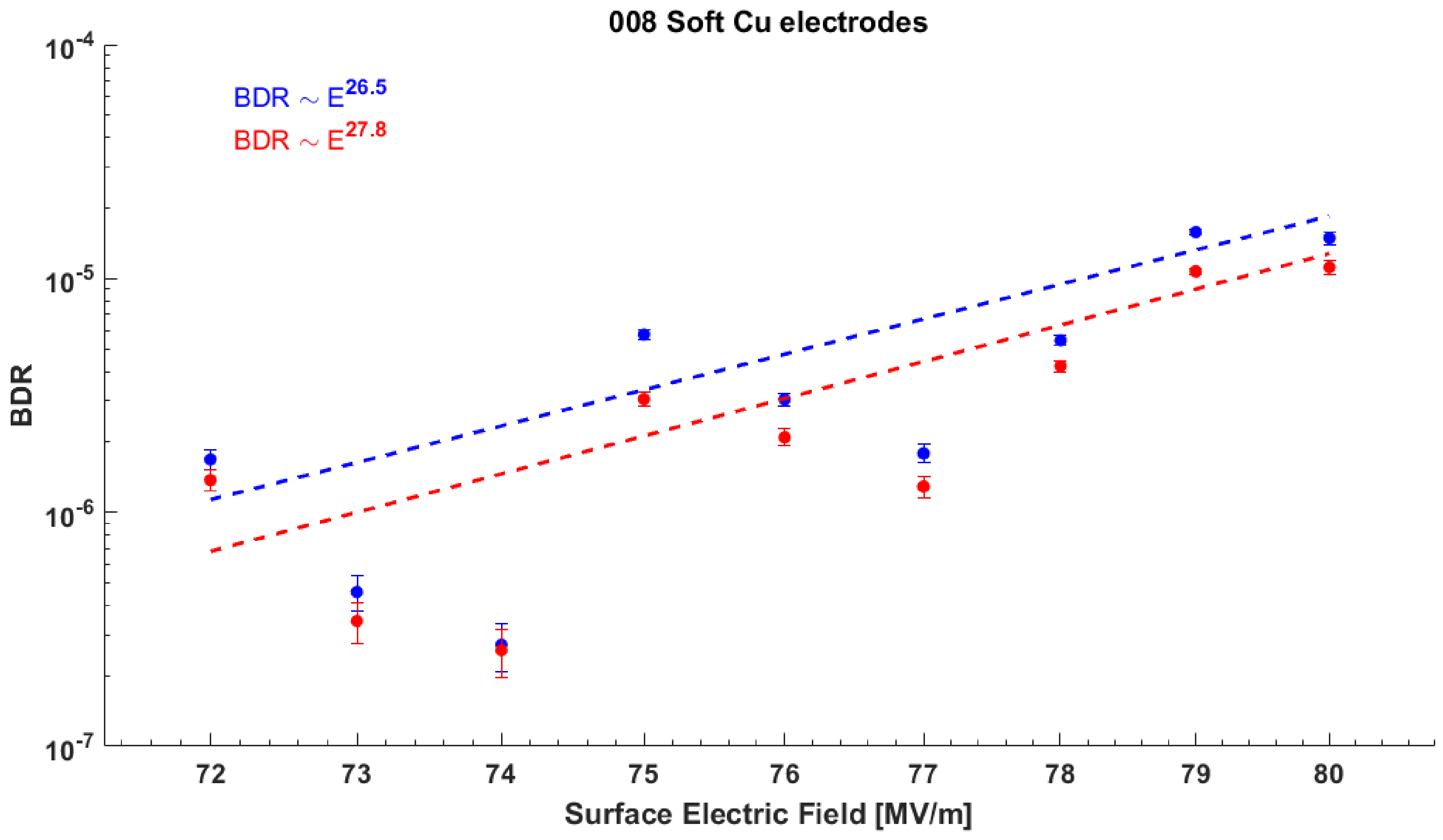


Fig. 17. Example of the fitting results for one of the test.

$$BDR \propto E^{\mathbf{30}}\tau^5$$

No.	Material	Surface Electric Field, MV/m	Power
005	SS CuAg	72.8 – 86.8	40
005	SS CuAg	87.8 – 102	39
006	Nb	65.0 – 89.0	13
006	Nb	75.0 – 103	14
007	Hard Cu	86 – 80	92
007	Hard Cu	85 – 77	54
008	Soft Cu	80 – 72	14
008	Soft Cu	72 – 80	27

BDR vs Pulse width

$$BDR \propto E^{30}\tau^{5}$$

Method of measurement:

- Choose voltage for BDR range 1E-4 – 1E-7.
- Choose pulse width for start.
- Start pulsing with 2 kHz.
- Change pulse width every N (~25 mln or 50 mln) number of pulses.

- The tests were done in the range 0.5 – 128 μs in increasing or decreasing order.

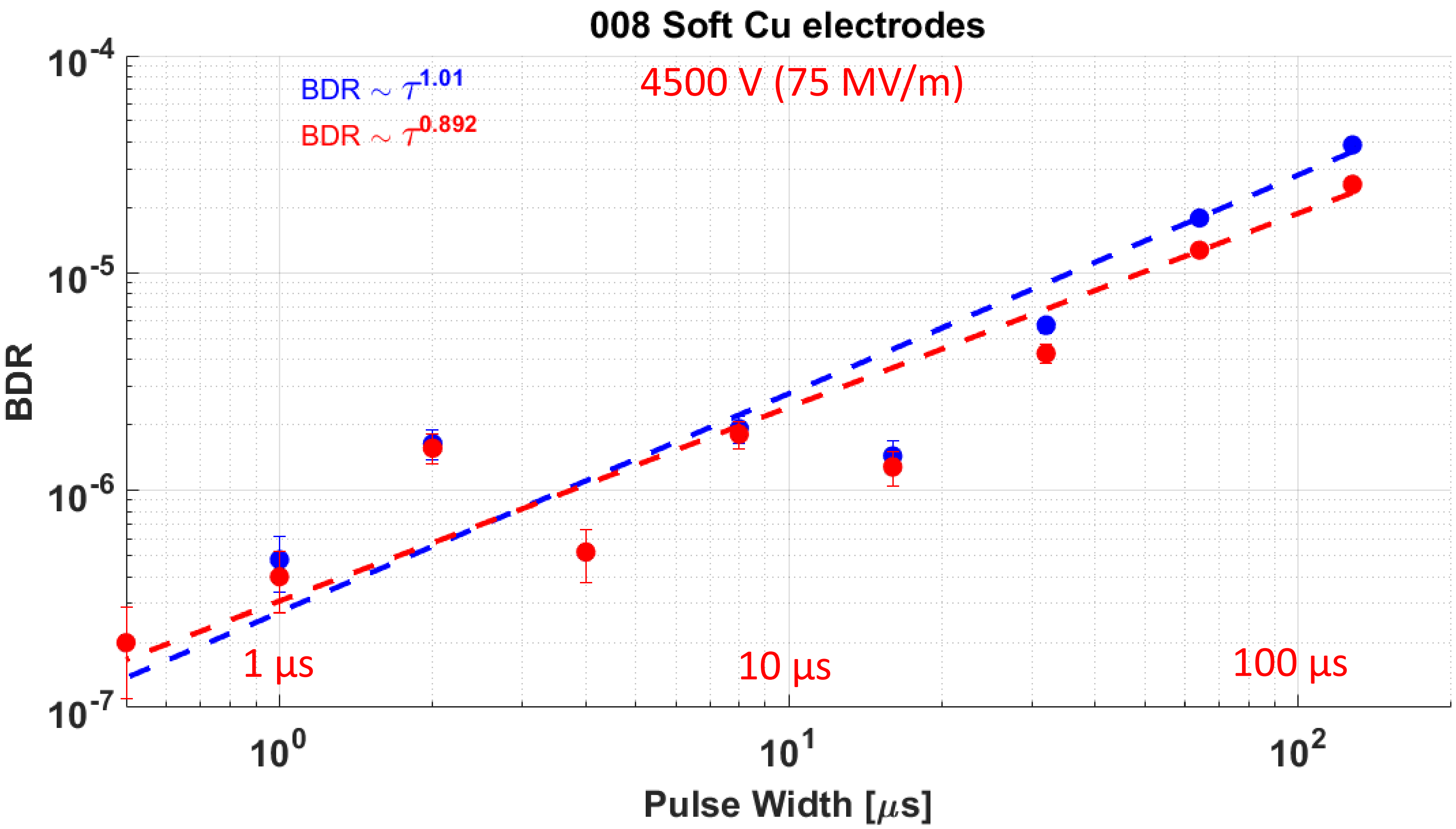


Fig. 18. Example of the fitting results for one of the test.

BDR vs Pulse width

$$BDR \propto E^{30}\tau^{5}$$

Table with results from all tests.

Sample number	Material	Range	Order	Voltage [V]	BDR range	Power
007	**Hard Cu**	0.5 - 64	up	4740	5.3E-6 – 4.3E-5	0.42
007	**Hard Cu**	0.5 - 128	down	4440	4.0E-7 – 1.7E-5	0.82
007	**Hard Cu**	0.5 - 128	up	4440	2.4E-7 – 1.3E-5	0.8
008	**Soft Cu**	0.5 - 128	up	4500	2.8E-7 – 2.2E-5	0.4
008	**Soft Cu**	0.5 - 128	down	4500	2.0E-7 – 3.0E-5	0.63
008	**Soft Cu**	0.5 - 128	down	4500	2.0E-7 – 3.9E-5	1.01
008	**Soft Cu**	0.5 - 128	up	4500	3.5E-7 – 3.7E-5	0.84

More data in Anton talk…

BDR vs Rep Rate

Motivation

To study the effect of Repetition Rate to the BD.

Methods

- The voltages was chosen to have BDR in reasonable range (1E-5 – 1E-7).
- The test were done with different electrodes (started with **005 SS CuAg** electrodes and the last results were taken few weeks ago with **012 Soft Cu**).

Step 1: Initial

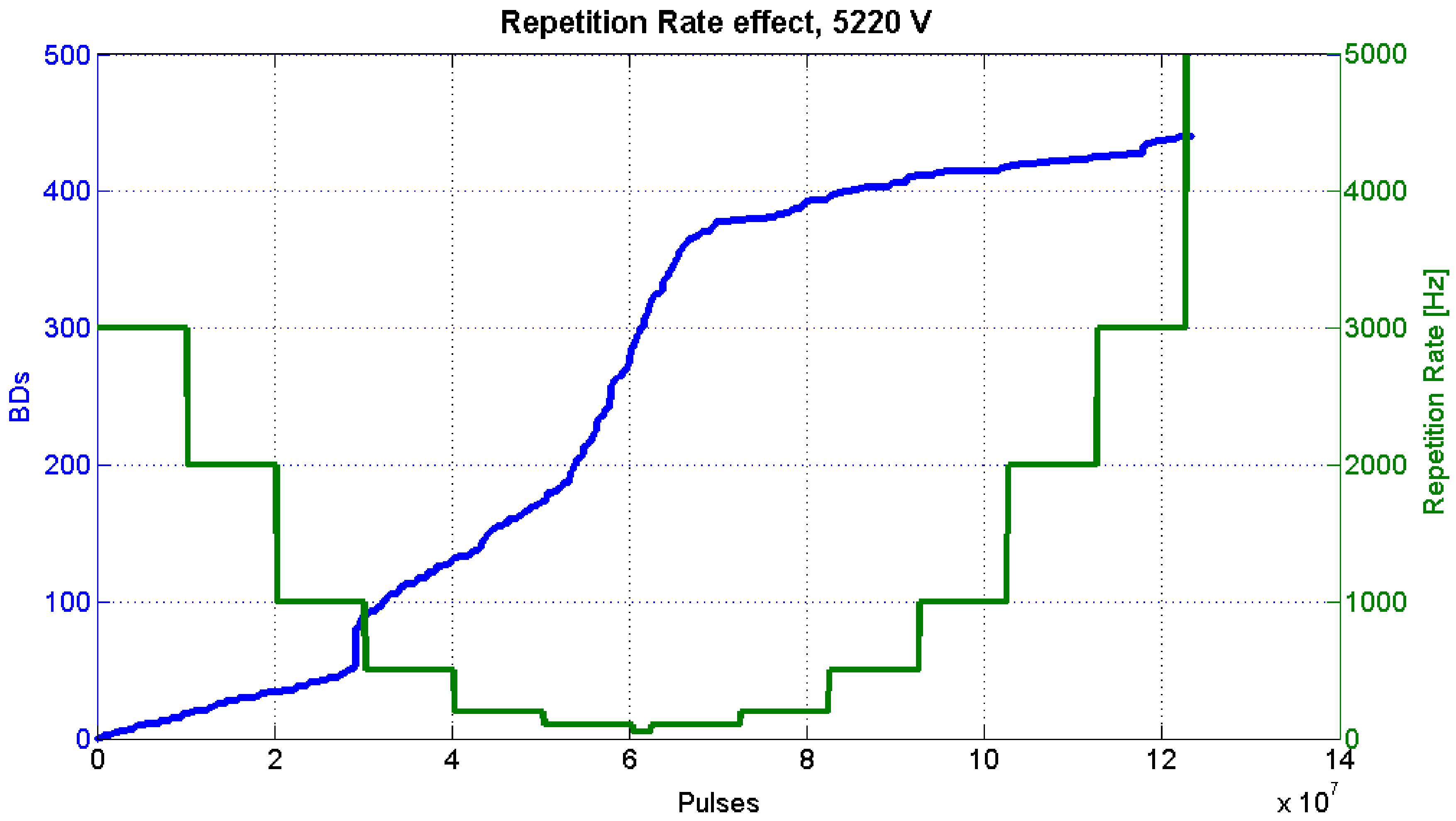


Fig. 21. BDs vs Pulses during test with different Repetition Rates.

Step 1: Initial

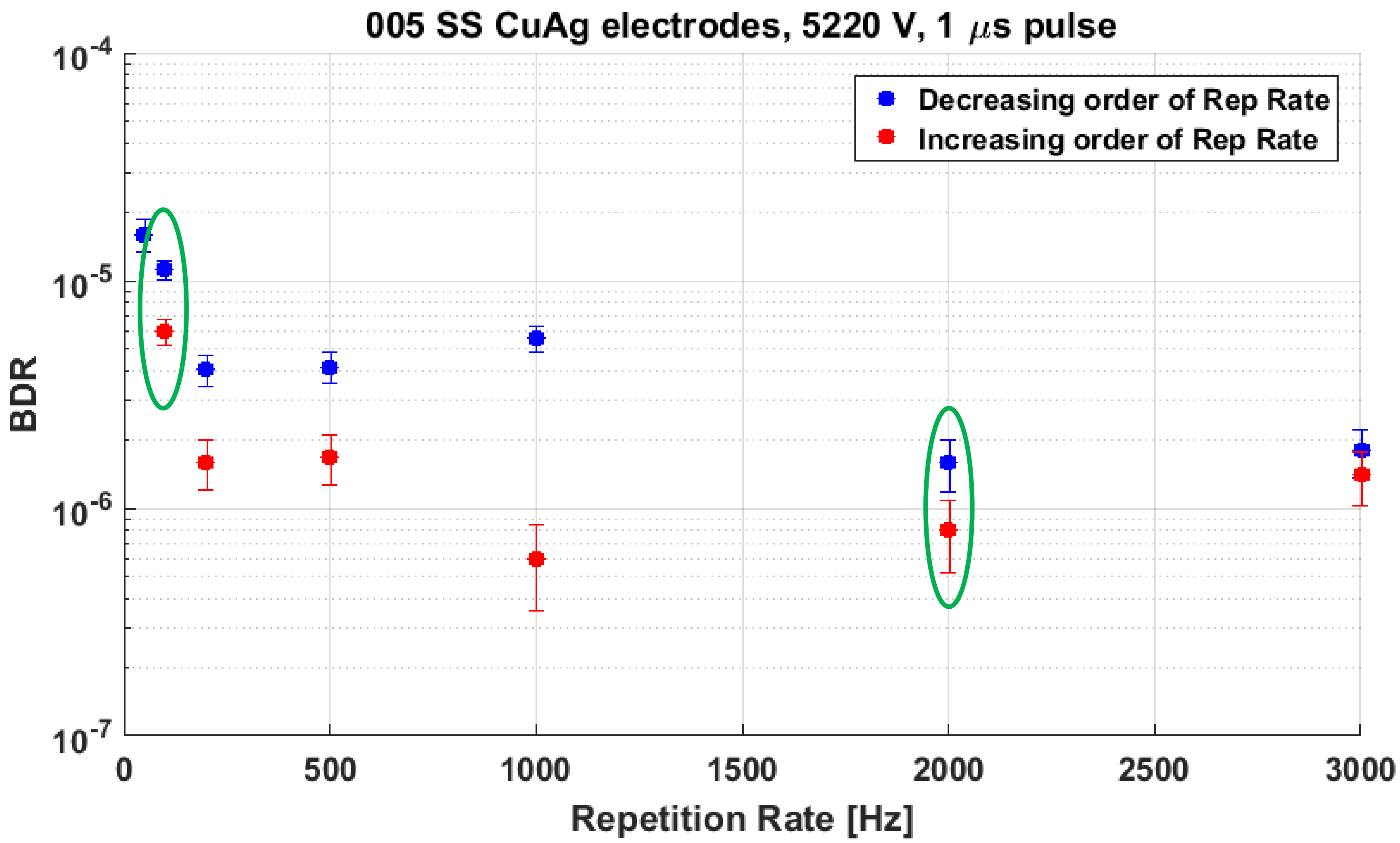
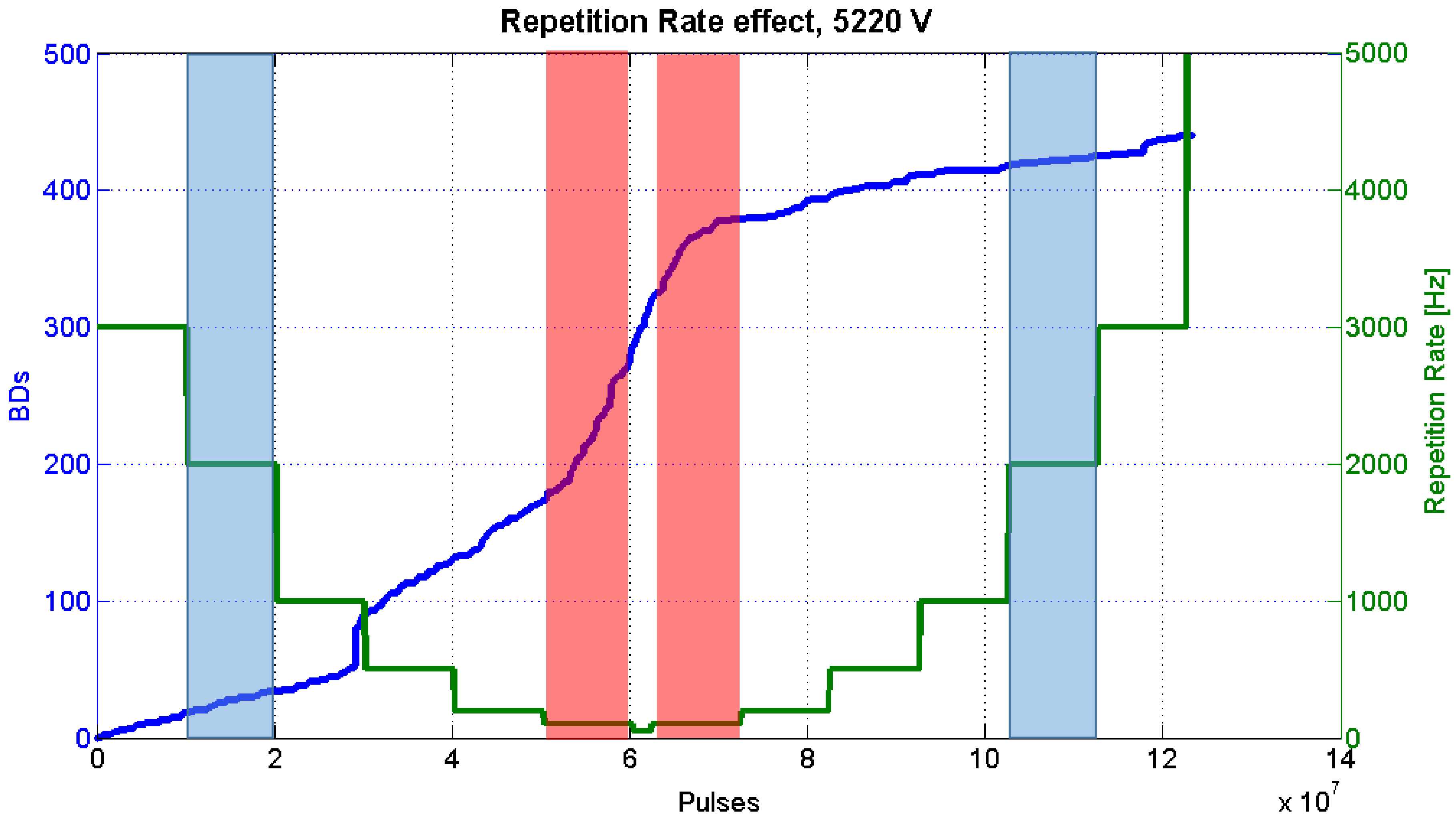


Fig. 22. BDR vs different Repetition rates.

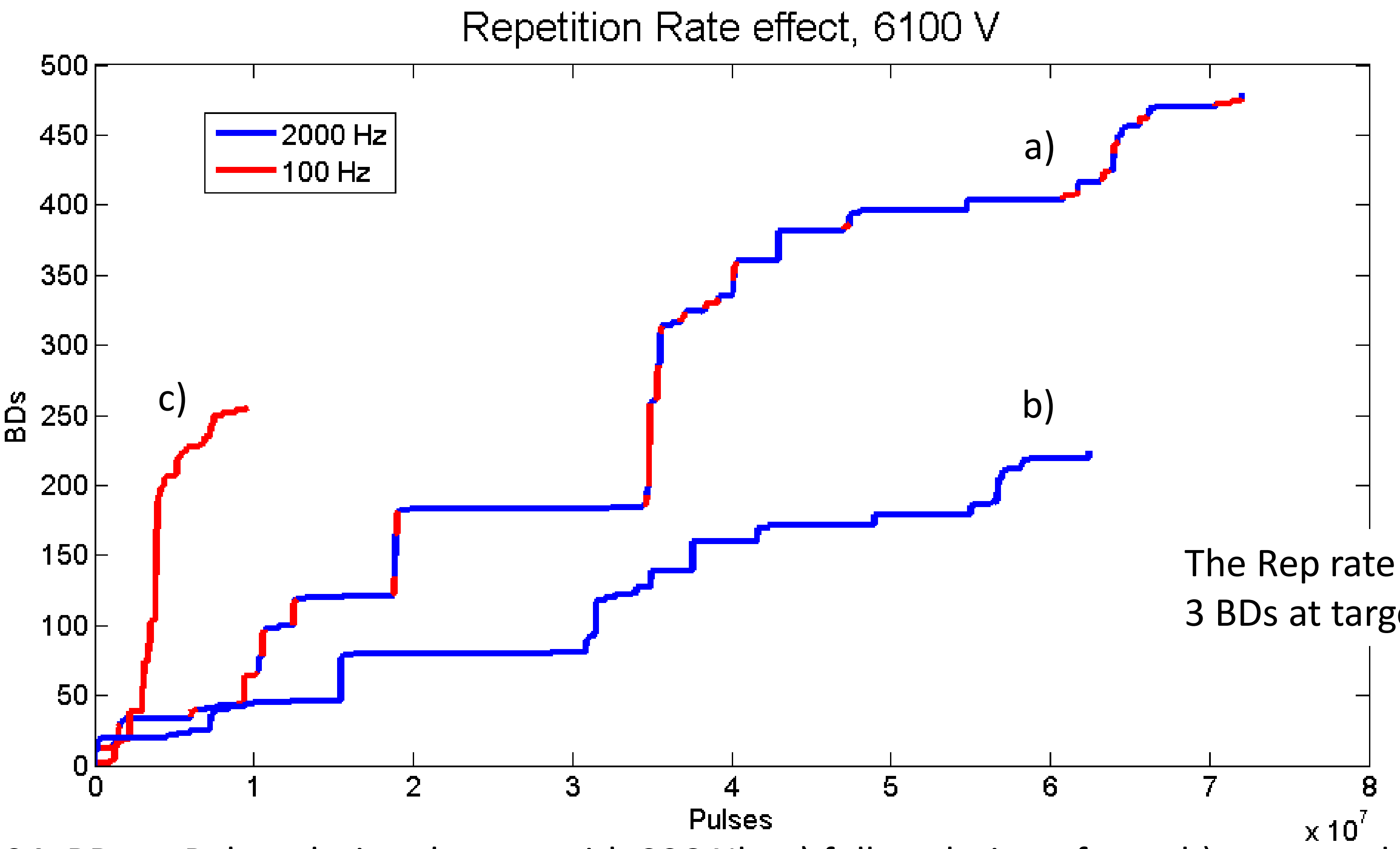
Step 1: Initial



For checking how difference in voltage could affect to the BDR, **100 Hz** and **2 kHz** results taken for comparison at next tests.

Fig. 23. BDs vs Pulses during test with different Repetition Rates.

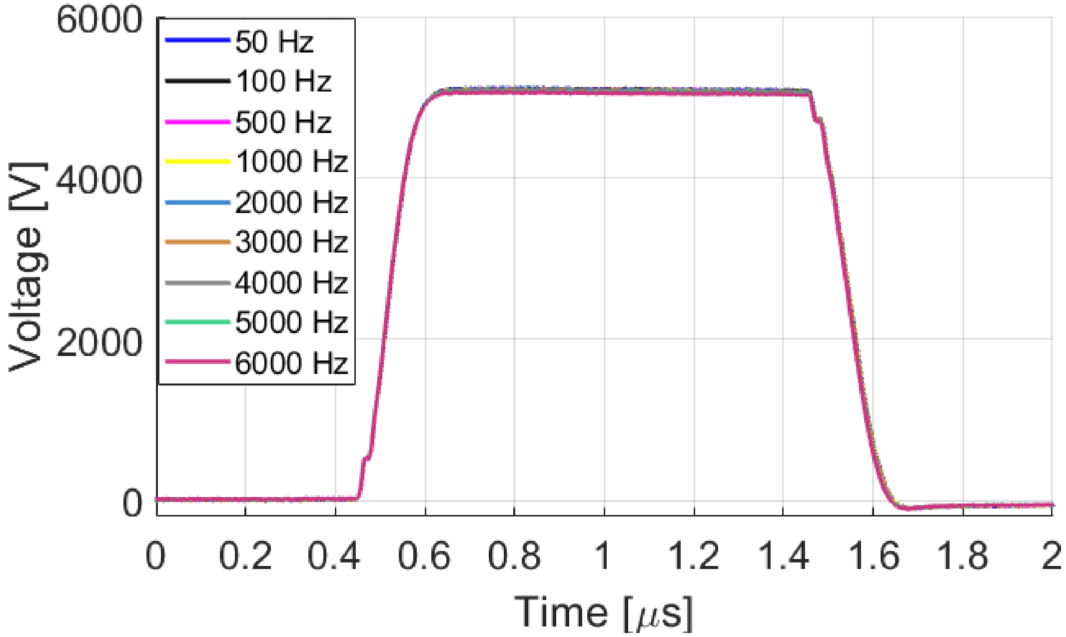
Step 2: Swap Rep Rates

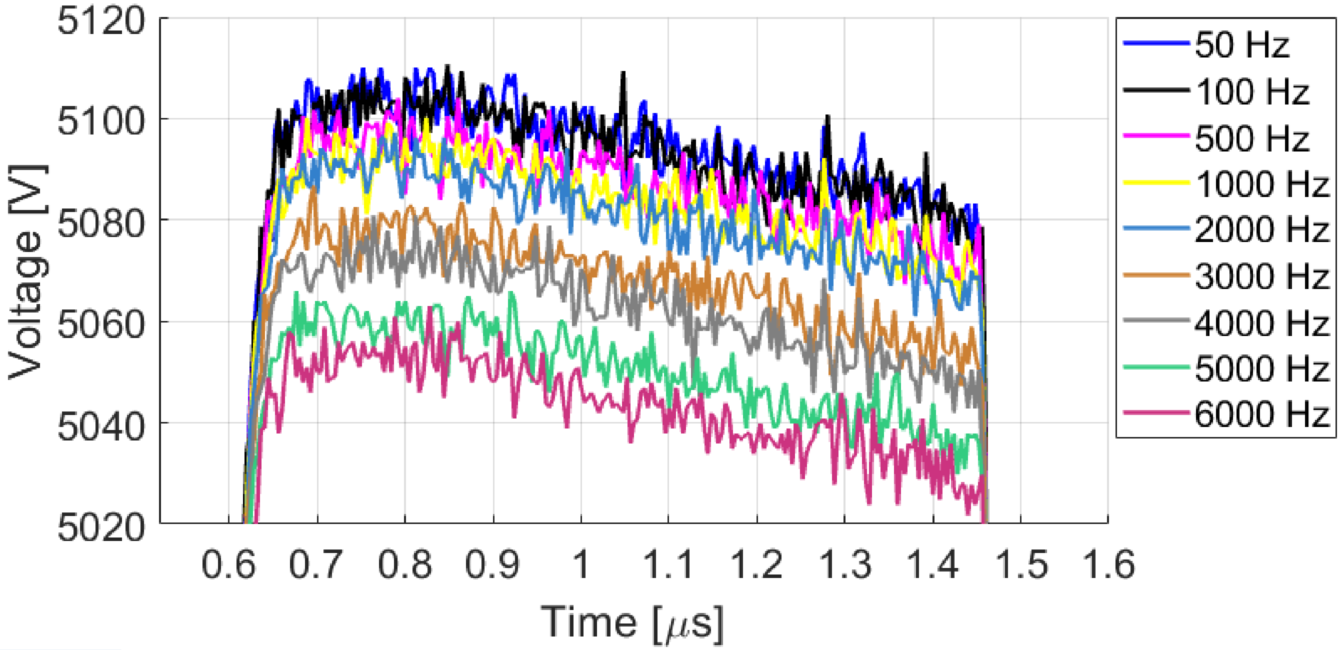


The Rep rate is changed every 3 BDs at target voltage

Fig. 24. BDs vs Pulses during the test with 006 Nb: a) full evolution of test; b) separated data taken with **2 kHz** during "a)"; c) separated data taken with **100 Hz** during "a)".

Step 3: Calibration





Vin = 400 V => Vout = 5100.5 V					
Rep Rate [Hz]	**MaxV**	**AmplV**	**AvrV**	**Abs rel 2000 Hz**	**Rel rel 2000 Hz**
50	5161	5114	5098	14	0.28%
100	5161	5109	5097	13	0.26%
500	5152	5105	5091	7	0.14%
1000	5144	5097	5087	3	0.06%
2000	**5146**	**5097**	**5084**	**0**	**0.00%**
3000	5132	5095	5072	-12	-0.24%
4000	5128	5073	5065	-19	-0.37%
5000	5106	5056	5053	-31	-0.61%
6000	5096	5050	5045	-39	-0.77%

Vin = 500 => Vout = 6396 V					
Rep Rate [Hz]	**MaxV**	**AmplV**	**AvrV**	**Abs rel 2000 Hz**	**Rel rel 2000 Hz**
50	6429	6396	6375	9	0.14%
100	6425	6392	6377	11	0.17%
500	6424	6391	6371	5	0.08%
1000	6421	6390	6369	3	0.05%
2000	**6425**	**6389**	**6366**	**0**	**0.00%**
3000	6418	6371	6357	-9	-0.14%
4000	6407	6363	6344	-22	-0.35%
5000	6399	6354	6336	-30	-0.47%
5000	6399	6354	6336	-30	-0.47%

Step 4: Swap Rep Rate vs correction

Sample number	Material	Rep Rate F1/F2	V1/V2	#BDs1/ #BDs2	BDR1/ BDR2	Ratio (BDR1/BDR2)
005	SS CuAg	100/2000	5220/5220	112/16	1.12E-5/1.59E-6	7.04
005	SS CuAg		5220/5220	60/8	5.98E-6/7.99E-7	7.48
006	Nb		6000/6000	198/201	3.99E-5/3.43E-6	11.63
006	Nb		6000/6000	255/224	2.66E-5/3.59E-6	7.41
007	Hard Cu		4520/4500	145/138	2.96E-5/1.89E-5	1.57
007	Hard Cu		4440/4460	87/96	1.63E-5/1.11E-5	1.47
007	Hard Cu		4380/4400	103/102	6.34E-6/3.34E-6	1.9
008	Soft Cu		4780/4800	195/156	1.99E-4/6.56E-5	3.03
008	Soft Cu		4600/4620	130/152	2.28E-5/6.9E-6	3.3
008	Soft Cu		4510/4530	77/83	1.96E-5/7.65E-6	2.56
008	Soft Cu		**4450/4570**	89/90	1.28E-5/7.89E-6	1.62
008	Soft Cu		4400/4420	145/133	1.38E-5/1.29E-6	10.7
004	SS and Cu		3760/3780	59/137	2.11E-6/1.12E-6	1.88

Step 5: Final

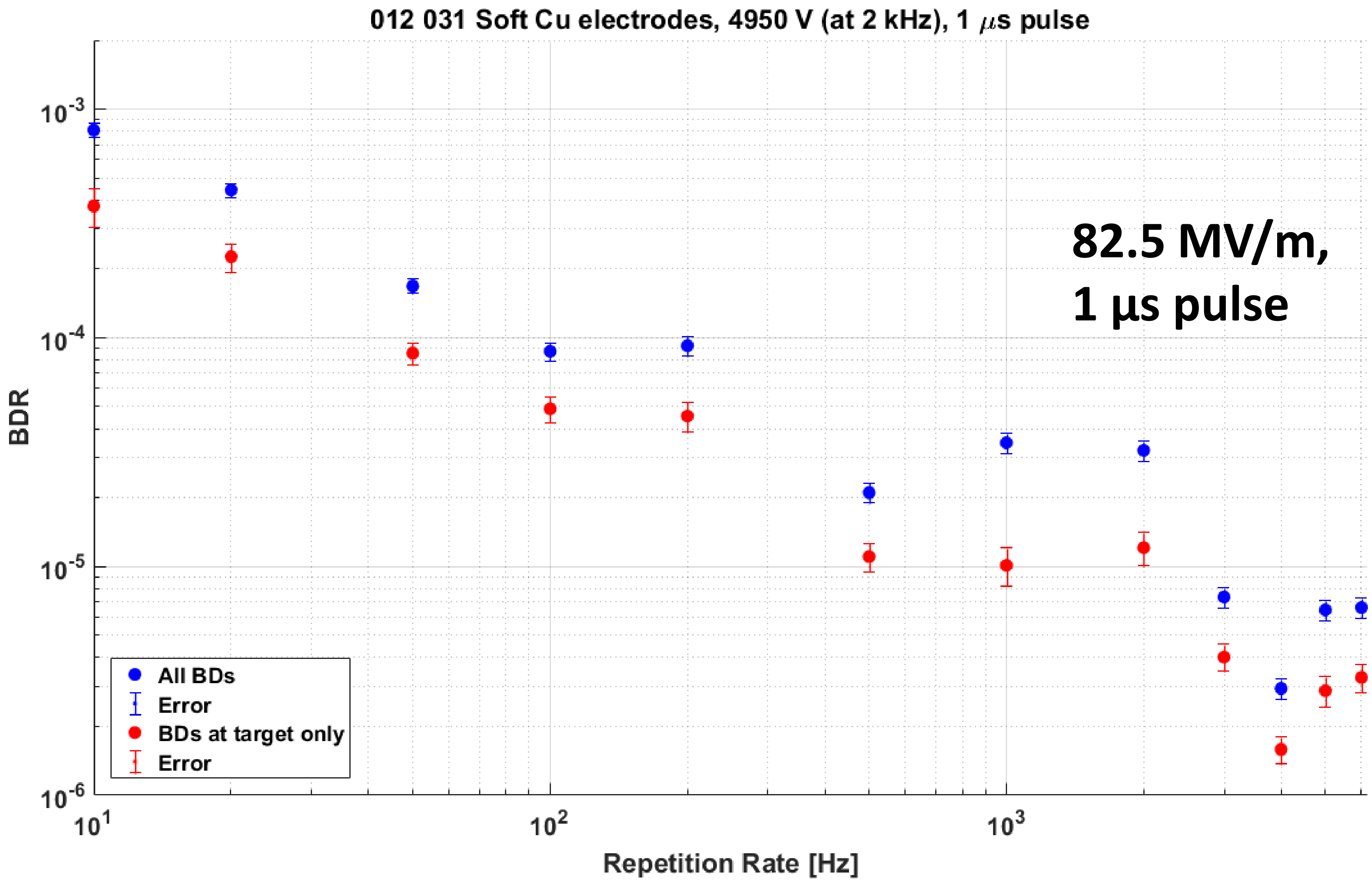
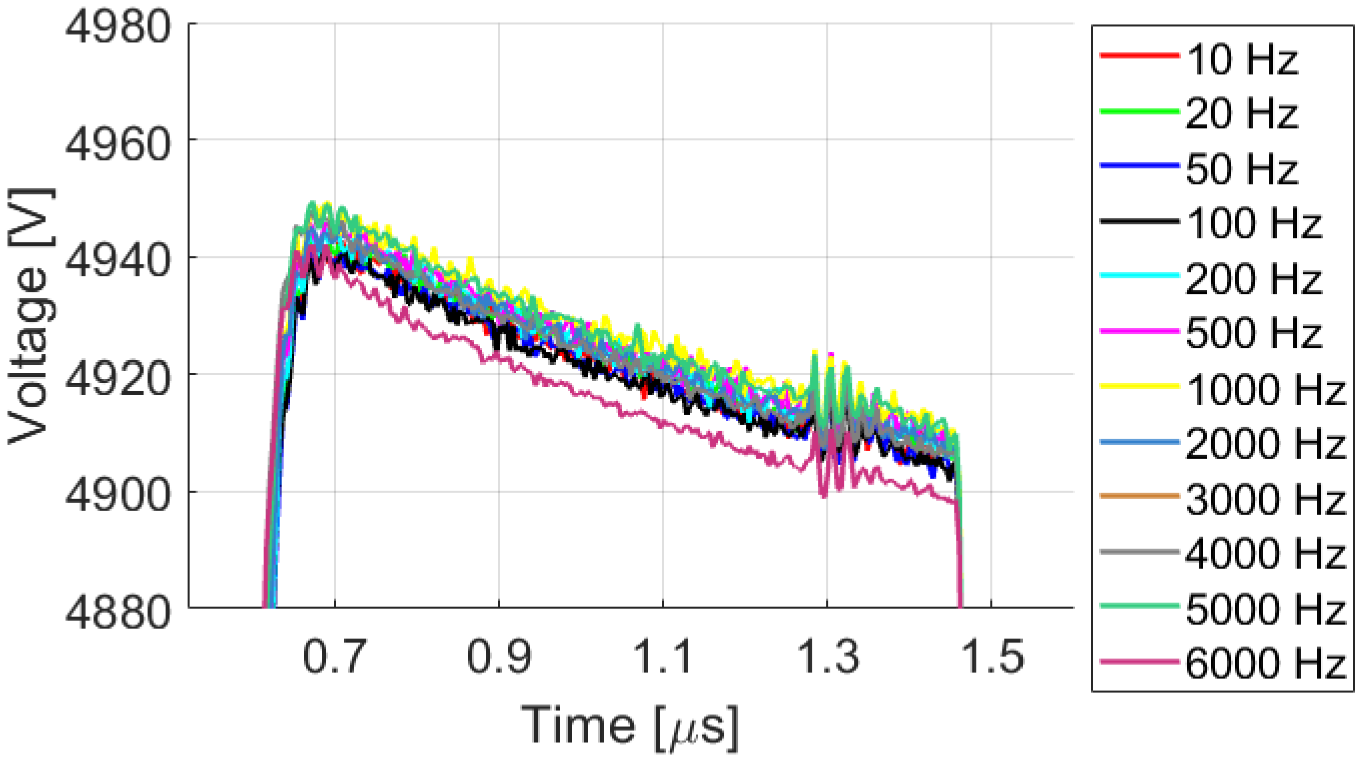


Fig. 27. The overview of the results from several cycles from 10 Hz to 6 kHz with compensation for voltages.

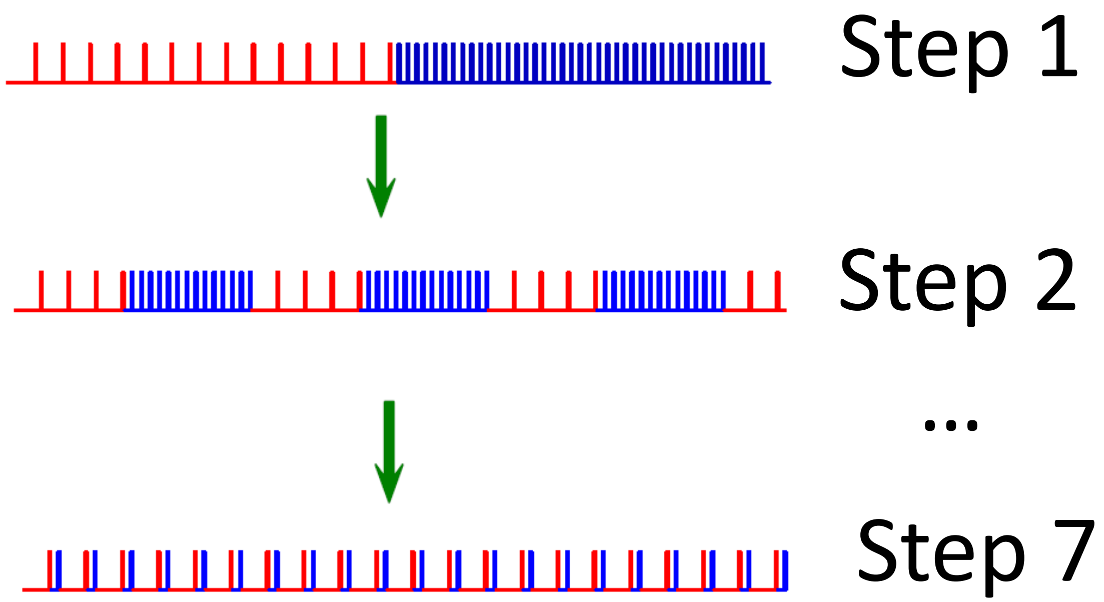
Step 6: Calibration for final test



Checking the applied correction for 4950 V.

Freq	AvrV	Abs rel 2000 Hz	Rel rel 2000 Hz
10	4925	-1.7	-0.03%
20	4926	-0.4	-0.01%
50	4924	-2.7	-0.05%
100	4923	-3.6	-0.07%
200	4927	0.5	0.01%
500	4928	1.4	0.03%
1000	4930	3.3	0.07%
2000	**4926**	**0.0**	**0.00%**
3000	4929	2.6	0.05%
4000	4926	-0.8	-0.02%
5000	4929	2.6	0.05%
6000	4918	-8.5	-0.17%

Step 7: Additional



Results for **009 Soft Cu** electrodes, 1 μs pulse width.

E field [MV/m]	Rep Rate, Hz	Pause before pulse, ms	BDs	BDR	BDR/ BDR
62	100	10	197	2.30E-05	1.63
	2000	0.5	121	1.41E-05	
61	100	10	116	9.30E-06	1.14
	2000	0.5	102	8.18E-06	
62	100	10	57	8.05E-06	1.46
	2000	0.5	39	5.51E-06	

Conclusion and future plans

- Two pulsed dc systems are available at CERN for studying conditioning process using different materials and effect of different parameters to BDR. Several tests are now standardized for each set of electrodes to help understanding the effect of the material.
- Correlation of data from different sources (generator, oscilloscope, vacuum gauge, cameras, microscopy) used to find full information for each BD.

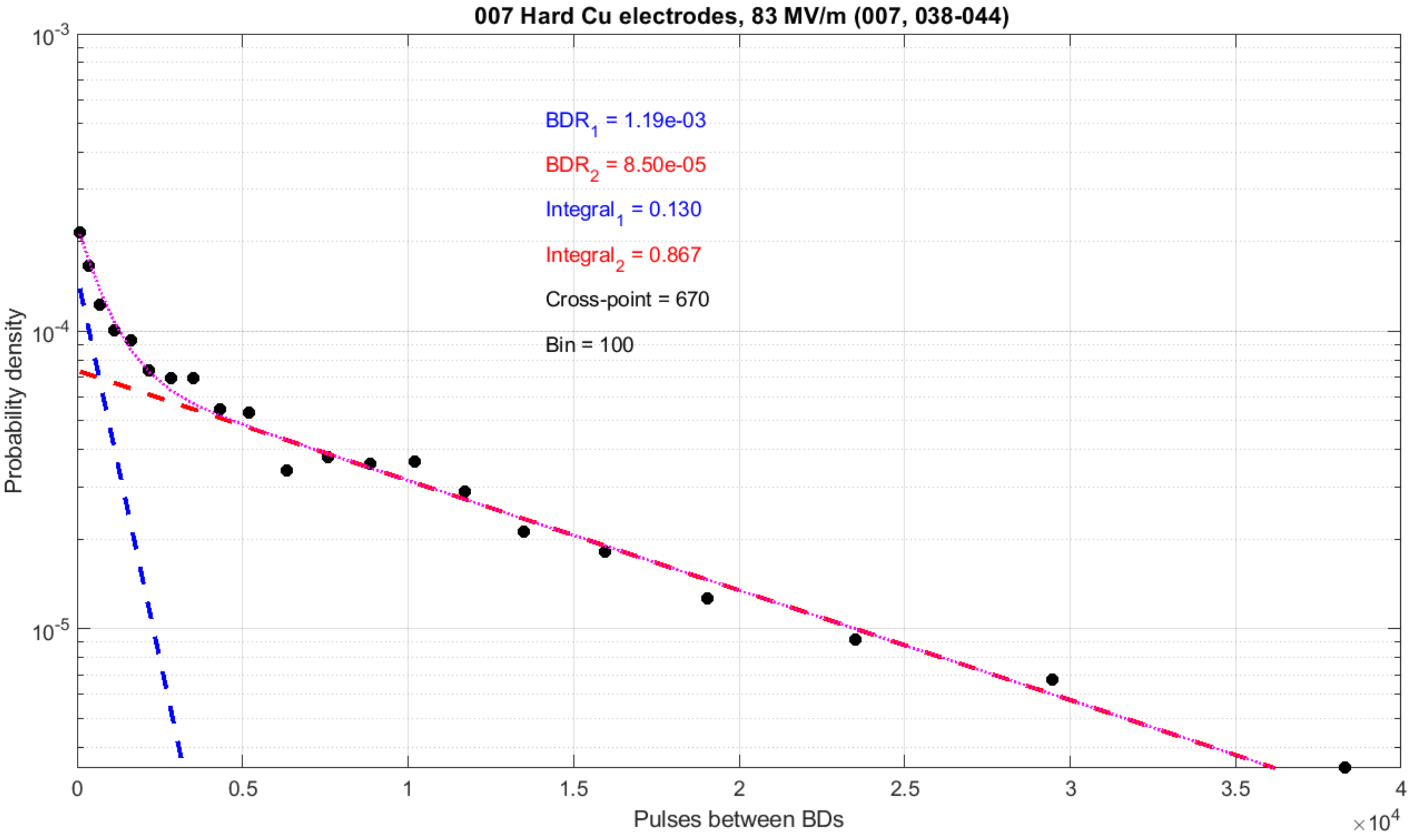
Plans:

- Provide fresh, half-conditioned and fully conditioned Soft Cu electrodes (for analysis @ Hebrew University of Jerusalem);
- Test with different gaps;
- Dark current measurement during the pulsing and looking for dark current fluctuations.

Any other ideas?

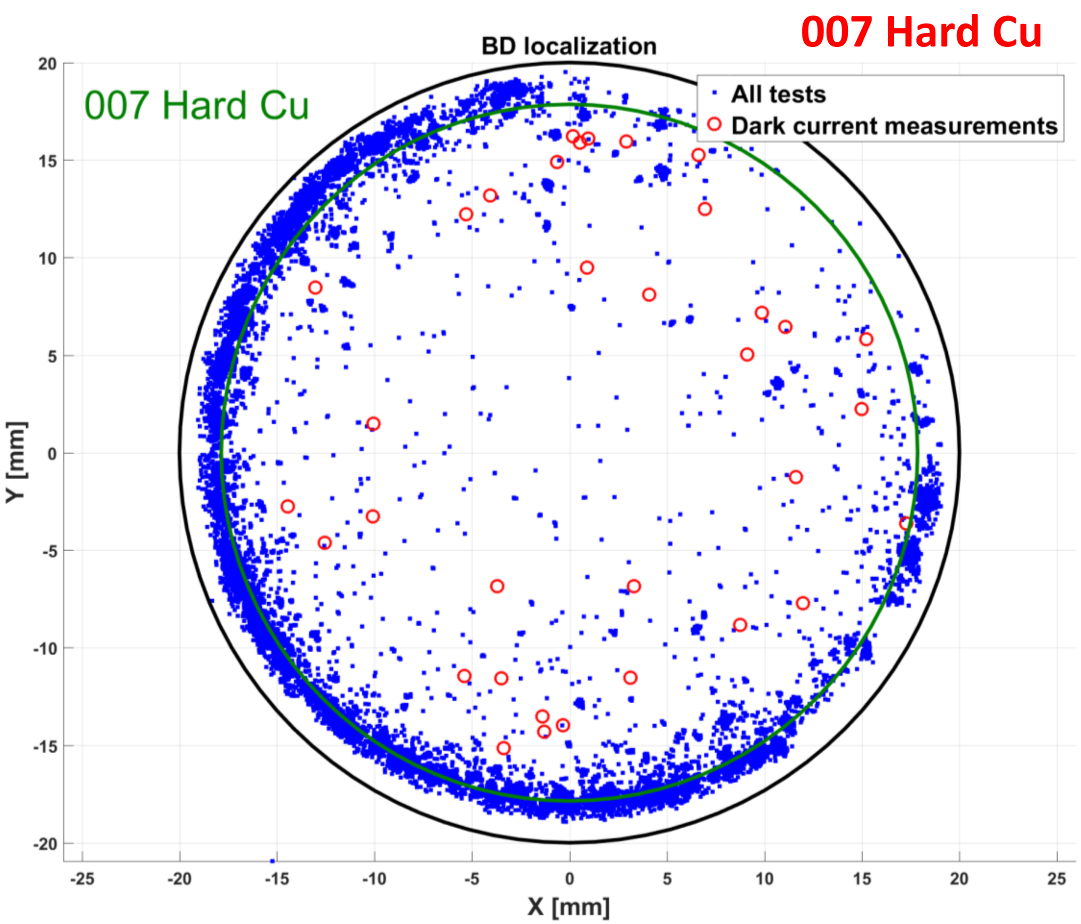
Extra slides

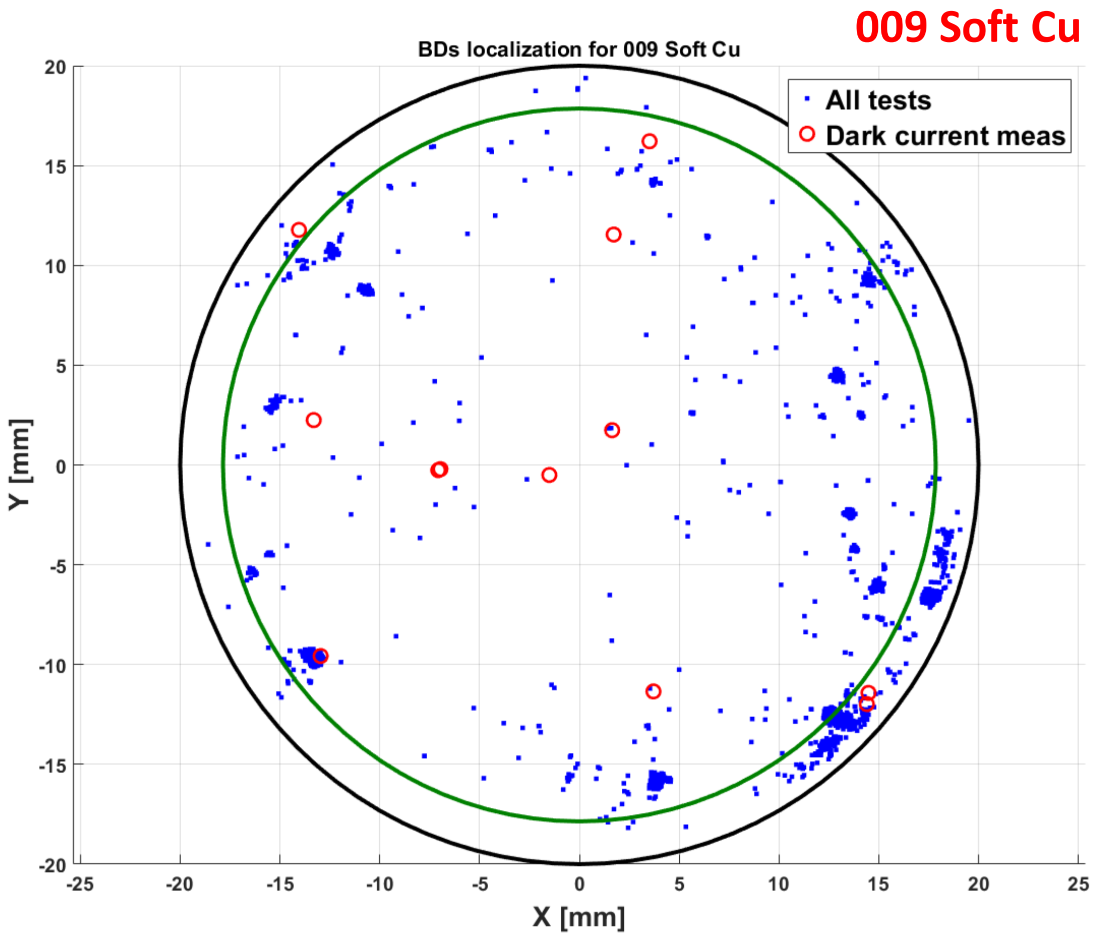
PDF



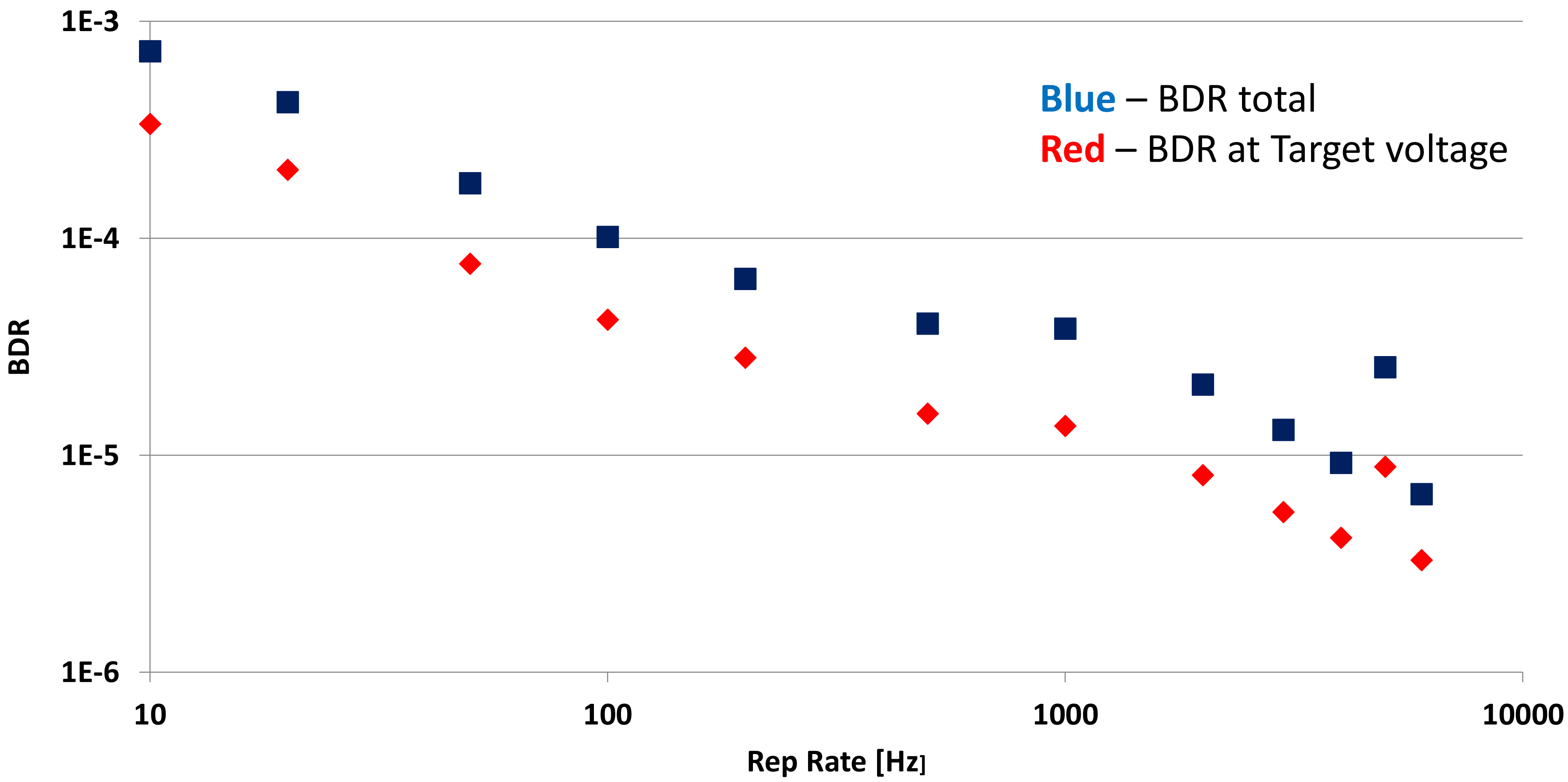
PDF without ramp data

BD localization



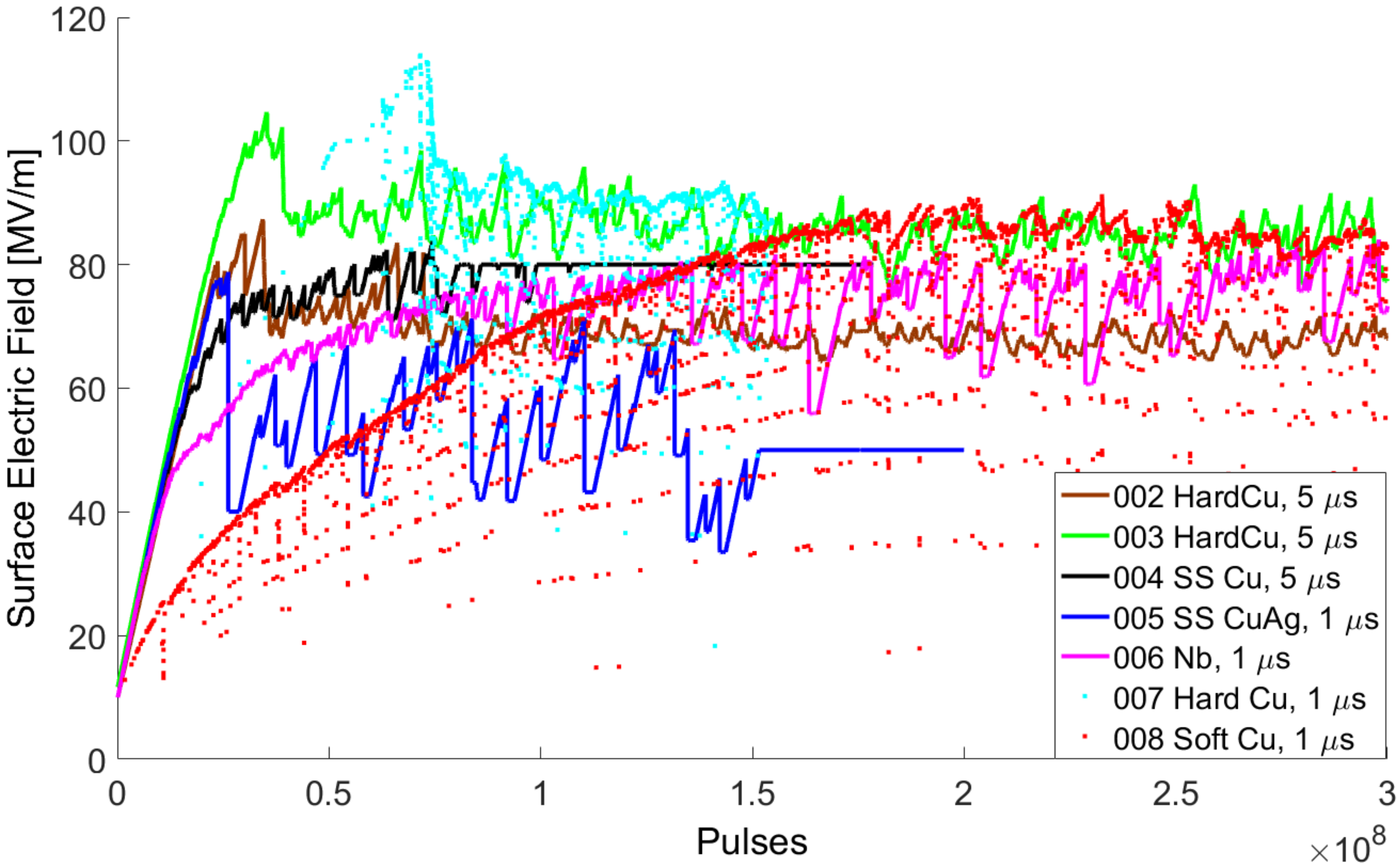


BD localization during all tests (in blue) and BDs during dark current measurements (in red) for: a) 007 Hard Cu, b) 009 Soft Cu electrodes. The start of edge at electrodes geometry is shown in green.



Summarized results from several tests with different Rep Rates

Conditioning for different materials



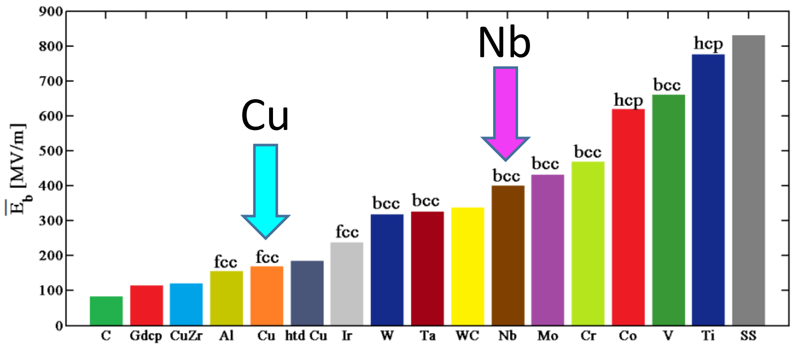
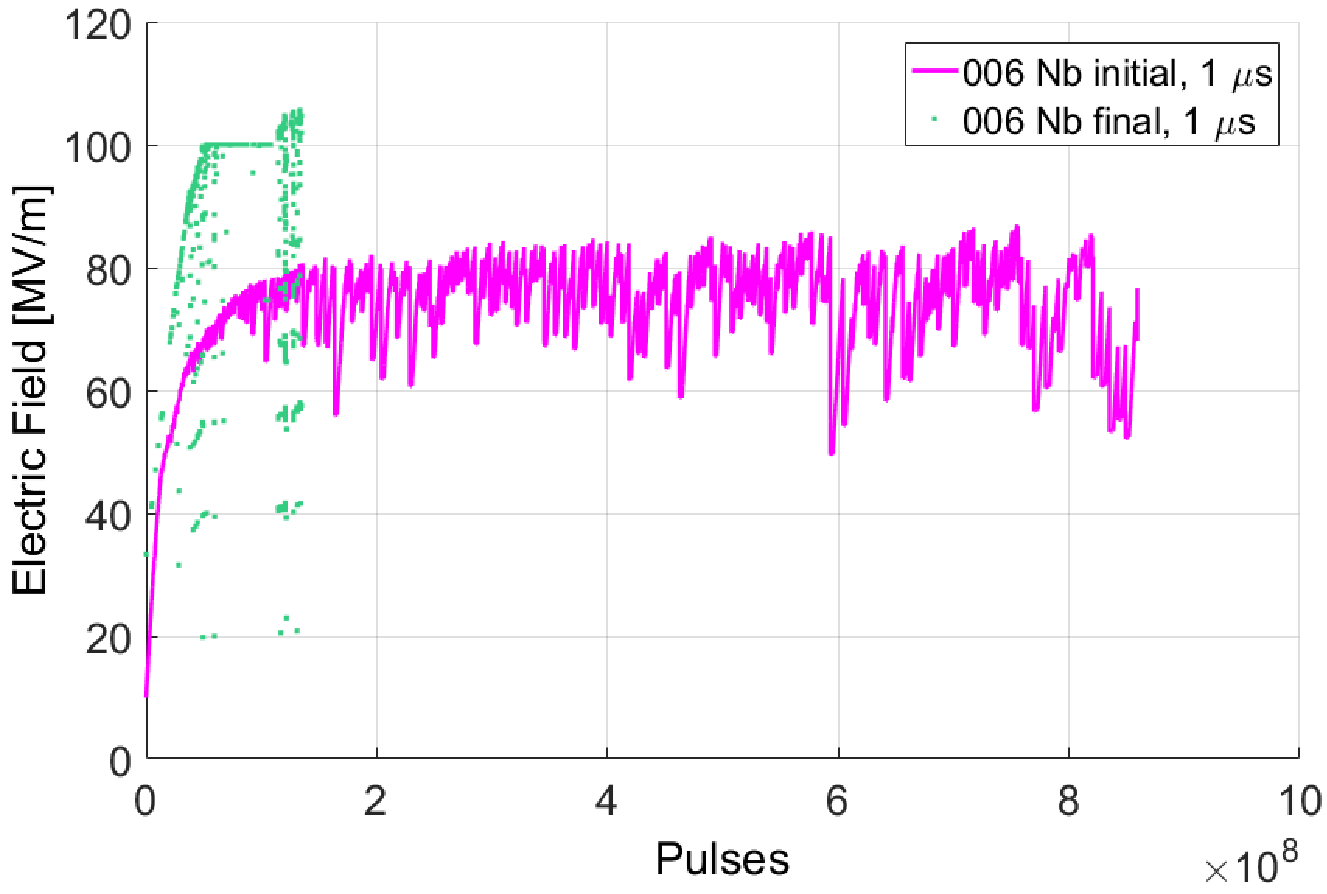


Figure 5: Average breakdown fields after conditioning of iridium shown with that of the materials previously tested in [1]. For pure metals, their crystal structures are indicated (fcc = face-centred cubic, bcc = body-centred cubic, hcp = hexagonal closest packing) on the top.

Fig. 36. Comparison of the conditioning for electrodes tested at pulsed DC systems. During all tests the spacer for 60 µm gap was used, except 002 Hard Cu (100 µm).

Initial and final conditioning for Nb



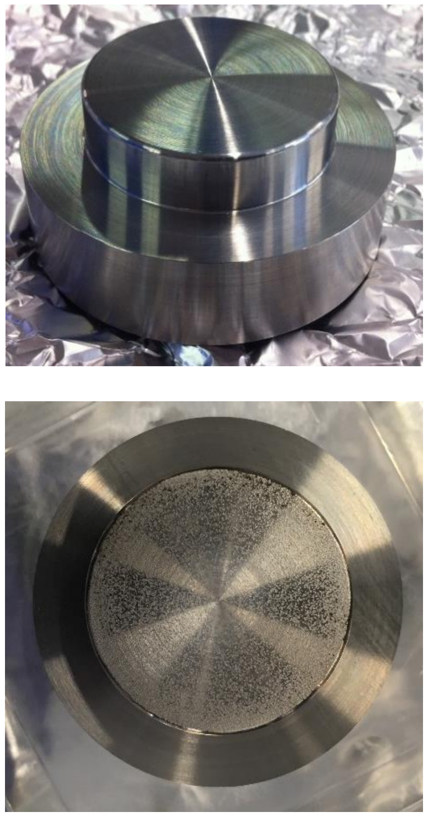
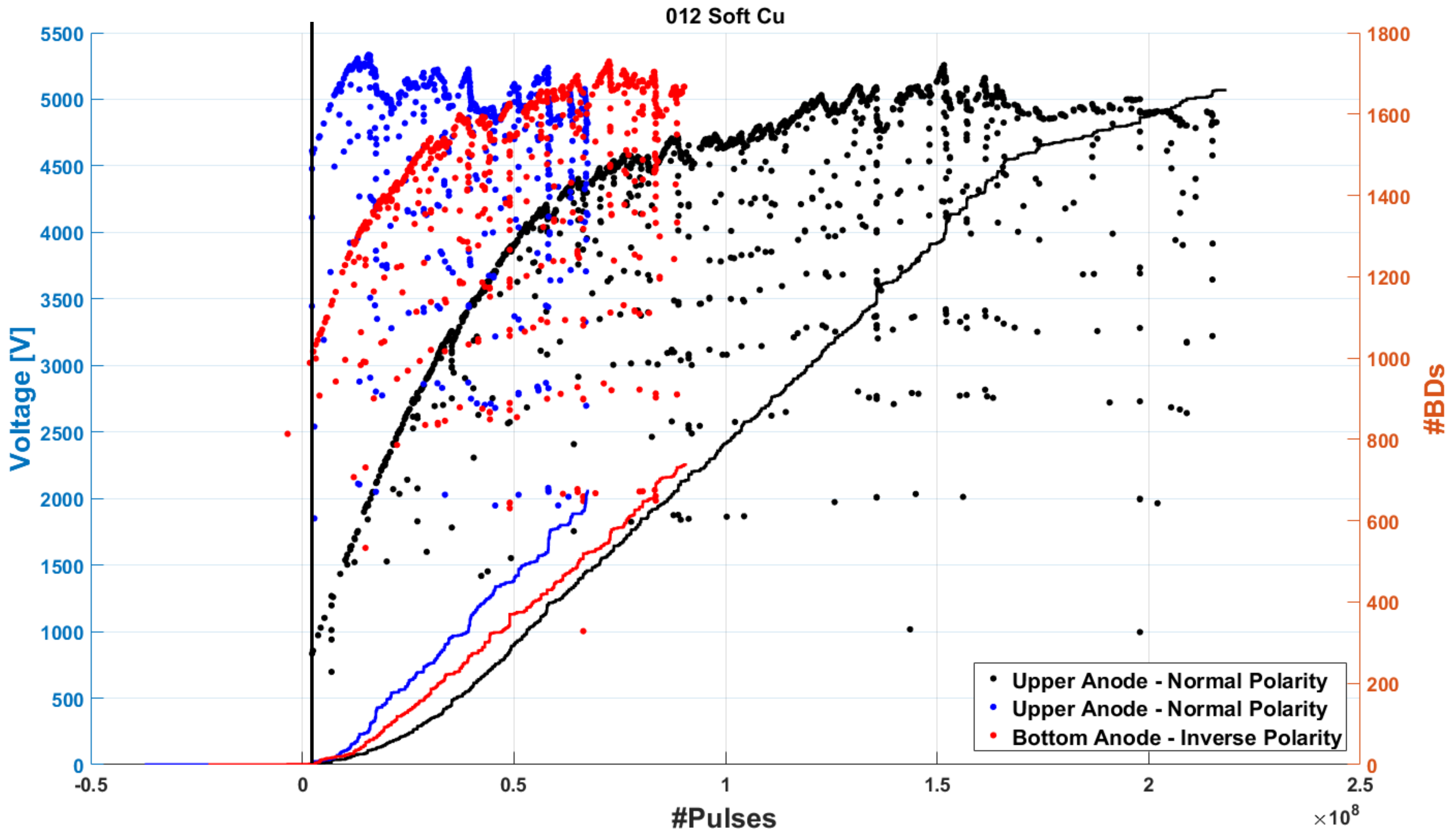


Fig. 23. Comparison of conditioning curves for 006 Nb electrodes.

Polarity changing



Distance vs Pulses between BDs